ELECTRIC RAILWAYS

A Series of Papers and Discussions Presented at the International Electrical Congress in St. Louis, 1904

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PREFACE.

The papers and discussions here reprinted define the state of the art of electric traction at the epoch of the St. Louis Exposition. The Electrical Congress of 1904 was in all respects valuable, but the papers on electric traction are particularly important, as marking the beginning of a new era — that of heavy railway work, with the introduction of single phase alternating motors. The valuable papers of Arnold, Dawson, Steinmetz, Deri, and others represent the new point of view which entirely changes the aspect of electric railway operation. For the previous decade the methods of electric traction had remained essentially unchanged. They had been stretched beyond the elastic limit, so to speak, in the endeavor to reach expanding conditions, and the logic of events demanded a change. The realization of this was strongly in evidence at the Congress of 1904, and the developments of the two years since passed have been directly along the lines then plainly foreseen. In fact, with few exceptions, the papers here presented bear the prophetic impress, and while the older methods found some vigorous support, the handwriting on the wall was plain for all to read. Achievement follows foresight, and commercial adaptation trails in the rear, so that one need not wonder at the apparently gradual progress in the actual equipment of roads. Such has been the history of other improvements, of the application of alternating currents to lighting and of polyphase cur-

rents to the electrical transmission of power. But methods inevitably change with the times, and one reading these papers half a dozen years hence will marvel, not so much at the insight of the engineers who wrote them, as that the work had already been so long delayed. Progress seems easy when viewed from a sufficient distance. This volume records the field notes of the advance guard.

LOUIS BELL.

BOSTON, MASS.

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ELECTRIC POWER TRANSMISSION COMMITTEE

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THE HISTORY AND DEVELOPMENT OF ELECTRIC RAILWAYS.

By FRANK J. SPRAGUE.

Although the earliest recorded experiments date back three-quarters of a century, the electric railway is essentially of modern development, for it achieved a recognized position less than twenty years ago, long after the telephone, the arc and incandescent lamp, and the stationary electric motor had been thoroughly established. This is but natural, for it is the logical outcome of the establishment of certain cardinal principles and practices in the kindred arts.

The first roads to carry passengers commercially were built in Europe, but the first railway experiments and the modern commercial impetus, as well as most of the essential and distinctive features of the art as it stands today, an example of almost unprecedented industrial development, are distinctively American.

Brandon, Vt., birthplace, and Thomas Davenport, blacksmith, father, are the names first on the genealogical tree of the electric railway, in the year 1834. A toy motor mounted on wheels, propelled on a few feet of circular railway by a primary battery, exhibited a year later at Springfield, and again at Boston, in the infant's photograph. This was only three years after Henry's invention of the motor, following Faraday's discovery ten years earlier that electricity could be used to produce continuous motion.

The records of Davenport's career, unearthed by the late Franklin Leonard Pope, show this early inventor a man of genius deserving a high place in the niche of fame, for in a period of six years he built more than a hundred operative electric motors of various

NOTE —The writer having been requested to prepare a paper on the subject of electric railways has done so with considerable reluctance because of his own connection with the art, and the difficulty under such circumstances in presenting events in a true perspective, unbiased by personal experiences. That such must be spoken of is, while embarassing, somewhat necessary, and due allowances should be made in his estimate of their importance.

designs, many of which were put into actual service, an achievement, taking into account the times, well nigh incredible.

For nearly two score years various inventors, handicapped with the limitations of the primary battery, and in utter ignorance of the principles of modern dynamo and motor construction, labored with small result. About 1838, a Scotchman, Robert Davidson of Aberdeen, began the construction of a locomotive driven by a motor similar to that used by Jacobi in his experiments on the river Neva, which was tried upon the Edinboro-Glasgow Railway, and attained a speed of about four miles an hour.

In an English patent issued to Henry Pinkus in 1840, the use of the rails for currents was indicated; also in a United States patent issued to Lilley and Colton of Pittsburg in 1847.

In 1847, Prof. Moses G. Farmer, late United States government electrician at the Newport Station, one of the most learned and able of the early electric experimenters, operated an experimental model car at Dover, N. H.; and about three years later one Thomas Hall exhibited in Boston an automatically reversing car mounted on rails through which current was supplied from a battery. These are said to be the first instances in which rails were actually used as carriers of the current, as well as the first time where there was a reduction by gear from the higher speed on the motor to the lower speed of the driven axle.

About the same time Prof. Page of the Smithsonian Institute, aided by a special grant from Congress, constructed a locomotive in which he used a double solenoid motor with reciprocating plunger and fly-wheel, as well as some other forms. This locomotive, driven by a battery of 100 Grove elements, was tried the 29th of April, 1851, upon a railroad running from Washington to Bladensburg, and attained a fair rate of speed.

Patents issued in 1855 to an Englishman named Swear and a Piemontais named Bessolo indicated the possibility of collecting current from a conductor suspended above the ground, and in 1864 a Frenchman named Cazal patented the application of an electric motor to the axle of the vehicle.

From the experiments of Farmer and Hall a decade elapsed before the invention by Pacinotti in 1861 of the continuous current dynamo, from which may properly be said to date all modern electric machines. These were developed in their earliest forms by Gramme and Siemens, Wheatstone and Varley, Farmer and Row-

land, Hefner-Alteneck and others, and brought into existence the elements essential to any possible commercial success. Yet notwithstanding that the principle of the reversibility of the dynamo-electric machine, and the transmission of energy to a distance by the use of two similar machines, said to have been discovered and described by Pacinotti in 1867 — the same year in which Prof. Farmer described the principle of the modern dynamo in a letter to Henry Wilde — and demonstrated independently at the Vienna Exposition by Fontaine and Gramme in 1873, many years more passed before the importance and availability of this principle were generally recognized.

From 1850 to 1875, is a long period, relatively, and yet there seemed to have been practically an entire cessation of experimental electric railway work, until in the latter year George F. Greene, a poor mechanic of Kalamazoo, Mich., built a small model motor which was supplied from a battery through an overhead line, with track return, and three years later he constructed another model on a larger scale. Greene seemed to have realized that a dynamo was essential to success, but he did not know how to make one, and did not have the means to buy it.

Shortly afterward, in 1879, at the Berlin Exposition, Messrs. Siemens and Halske constructed a short line about a third of a mile in length, which was the beginning of much active work by this firm. The dynamo and motor were of the now well-known Siemens type, and the current was supplied through a central rail, with the running rails as a return, to a small locomotive on which the motor was carried longitudinally, motion being transmitted through spur and beveled gears to a central shaft from which connection was made to the wheels. The locomotive drew three small cars having a capacity of about 20 people, and attained the speed of about eight miles an hour.

In the same year important experiments were carried on by Messrs. Felix and Chretien at the little village of Sermaize in France to demonstrate the possibilities of the transmission of energy.

At Vienna in the following year, Egger exhibited a model of an electric railway, the current to be supplied through the running rails. About the same time Messrs. Bontemps and Desprez made a study of a scheme for replacing pneumatic transmission of dispatches by miniature electric locomotives in Paris.

The Siemens and Halske demonstration in Berlin was followed by others for exhibition purposes at Brussels, Dusseldorf and Frankfort, but no regular line was established until a short one with one motor car at Lichterfelde, near Berlin, the first in Europe, or in fact in the world. This road was 1 1/2 miles in length, used all rail conductors, and was opened for traffic in May, 1881.

The motor was carried on a frame underneath the car between the wheels, and current transmitted from the armature to drums on the axles by steel cables. The car was of fair size, having a capacity of 36 passengers, and attained a maximum speed of about 30 miles. The e.m.f. used was about 100 volts. This line was continued in regular service, but 12 years later the rail method of distribution was replaced by two conductors carried on top of poles, upon which ran a small carriage connected to the gear by a flexible cable.

Shortly afterward the same firm installed at the Paris Electrical Exposition of 1881, a small tramway about a third of a mile long, and used for the first time overhead distribution. In this case the conductors consisted of two tubes slotted on the under side, and supported by wooden insulators. In the tubes slid shoes which were held in good contact by an underrunning wheel pressed up by springs carried on a frame-work supported by the conductors, and connected to the car by flexible conductors. The motor was placed between the wheels, and the power was transmitted by a chain.

About the same time Siemens constructed an experimental road near Meran in the Tyrol with a view of demonstrating the possibilities of electric traction for the San Gothard tunnel, and later other small lines at Frankfort, Molding and elsewhere. These were followed by a comprehensive scheme for a combined elevated and underground road submitted to the city authorities at Vienna.

The invention about this time of accumulators directed attention to the possibilities of the self-contained car, and in 1880 a locomotive with accumulators was used at the establishment of Duchesne-Fournet at Breuil, and in the following year Raffard with a large battery of Faure accumulators made experiments on the tramway at Vincennes.

In 1881, Dr. John Hopkinson, in describing the application of motors to hoists, proposed both for them and for tramways the simple series-parallel control for speed, a principle which combined with resistance variation later became universal.

Meanwhile in the United States two inventors, Stephen D. Field and Thomas A. Edison, began electric experiments almost simultaneously. Edison was perhaps nearer than any other on the verge of great possibilities had it not been that he was intensely absorbed in the development of the electric light, for he had in the face of much adverse criticism developed the essentials of the low internal resistance dynamo with high-resistance field, and many of the essential features of the multiple arc system of distribution. In fact, in 1880 he built a small road at his laboratory at Menlo Park, on which he ran a car operated by one of his earliest dynamos from which the power was transmitted to the axle by a belt. One set of wheels was insulated, and the two rails were used for current. But beyond taking out a few patents, and for a while acting in conjunction with Field, Edison did little in this particular field, and soon ceased to be a factor.

Perhaps more than to any other the credit for the first serious proposal in the United States should be awarded to Field. Curiously enough, patent papers were filed by Field, Siemens and Edison, all within three months of each other in the spring and summer of 1880. Priority of invention was finally awarded to Field, he having filed a caveat a year before. He had been actively interested in electric telegraphs, and in an account of his work published some 20 years ago, it is stated that he early constructed two electric motors, and had in mind the operation of street cars in San Francisco, but had not been able to do anything in the matter because of a realization that a dynamo must be used instead of a battery. In 1877 while in Europe he saw some Gramme machines, and on his return two of them were ordered but not delivered. Later a dynamo was ordered from Siemens Brothers in London which was lost, and this was replaced by another which arrived in the fall of 1878. Meanwhile two Gramme machines were placed at his disposal, and shortly afterward an electric elevator was operated. In February, 1879, he made plans for an electric railway, the current to be delivered from a stationary source of power through a wire enclosed in a conduit, with rail return, and in 1880–81, he constructed and put in operation an experimental electric locomotive in Stockbridge, Mass.

Pending the settlement of patent interferences between Edison and Field (the Siemens application being late was rejected), the two interests were combined in a corporation known as "The Electric Railway Company of the United States," and the first work of

the company was the operation of an electric locomotive at the Chicago Railway Exposition in 1883. This locomotive called "The Judge," after the late Chief Justice Field, ran around the gallery of the main exposition building on a track of about one-third of a mile in length. The motor used was a Weston dynamo mounted on the car and connected by beveled gear to a shaft from which power was transmitted by belts to one of the wheels. The current was taken from a center rail, with track return. A lever operated clutches on the driving shaft, and the speed was varied by resistance. The reversing mechanism consisted of two movable brushholder arms geared to a disk operated by a lever, each arm carrying a pair of brushes one of which only could be thown into circuit at a time, to give the proper direction of movement.

Meanwhile several other inventors were getting actively into the field of transmission of power and electric railways. In the summer of 1882, Dr. Joseph R. Finney operated in Allegheny, Pa., a car for which current was supplied through an overhead wire on which traveled a small trolley connected to the car with a flexible cable, and about the same time in England Dr. Fleming Jenkin, following a paper by Messrs. Ayrton and Perry before the Royal Institution on an automatic railway, proposed a scheme of telpherage which was developed by those gentlemen.

In the early part of the same year, the writer, then a midshipman in the United States Navy, who had in 1879 and 1880 begun the designing of motors, was ordered on duty at the Crystal Palace Electrical Exhibition, then being held at Sydenham, England. While in London he became impressed with a belief in the possibility of operating the underground railway electrically. He first considered the use of main and working conductors, the latter being carried between the tracks, with rail return, but noting the complication of switches on certain sections of the road, conceived the idea of a car moving between two planes, traveling on one and making upper pressure contact with the other, those planes being the terminals of a constant potential system. For practical application the lower of the two planes was to be replaced by the running track and all switches and sidings, and the upper plane by rigid conductors supported by the roof of the tunnel, and following the center lines of all tracks and switches, contact to be made therewith by a self-adjusting device carried on the car roof over the center of the truck and pressed upward by springs.

In 1882 he applied for a patent on the first idea, which was but a variation from that shown in other patents, but the second laid dormant for nearly three years because of central station work and the development of the application of stationary motors.

The storage battery still attracted attention, and in 1883 experiments were carried on at Kew Bridge, London. In the latter part of 1884 the Electrical Power & Storage Company of London, under the direction of Anthony Reckenzaun, began a number of trials. The same engineer repeated his work at Mill Wall, and later in Berlin. The car body in his last experiment was carried by two trucks, each of which was equipped with a motor driving one axle through a worm gear. Reversal was accomplished by using two sets of brushes, and speed was varied by using one or both motors, also by using the motors in series or parallel with a resistance to cut down sparking when making the change over.

Reckenzaun subsequently had charge of the experiments conducted by Wm. Wharton of Philadelphia, in which both a Reckenzaun and a Sprague motor were used in 1886. Here series parallel grouping of both batteries and motor circuits were used on the Sprague car, and a series parallel and resistance variation of motors on the car operated by Reckenzaun and Condict.

Meanwhile, in the United States, Charles J. Van Depoele, a Belgian by birth and a sculptor by original trade, and an indefatigable worker, had become interested in electric manufacturing, and soon energetically attacked the railway problem. His first railway was a small experimental line constructed in Chicago in the winter of 1882–83, the current being supplied from an overhead wire. In the fall of 1883, a car was also run at the Industrial Exposition at Chicago.

A year later a train pulled by a locomotive car, and taking current from an underground conduit, was successfully operated at the Toronto Exhibition to carry passengers from the street car system, and again in the year following Van Depoele operated another train at the same place, using on this occasion an overhead wire and a weighted arm pressing a contact up against it.

Experiments were also carried on by him on the South Bend Railway in the fall of 1885, where several cars were equipped with small motors, and also in Minneapolis, where an electric car took the place of a steam locomotive. Other equipments were operated at the New Orleans Exhibition, and at Montgomery, Ala., where the

current was at first taken from a single-overhead wire which carried a traveling trolley connected to the car by a flexible conductor.

Other equipments were put in operation at Windsor, Ont., Detroit, Mich., Appleton, Wis., and Scranton, Pa.

In these several equipments the motors were placed on the front platforms of the cars, and connected to the wheels by belts or chains. The cars were headed in one direction, and operated from one end only.

In 1888, the Van Depoele Company was absorbed by the Thomson-Houston, which had recently entered the railway field, and Van Depoele continued in its active development until his death in 1892.

Among the early American workers of this period, none was for a time more prominent than Leo Daft, who after considerable development in motors for stationary work took up their application to electric railways, making the first experiments toward the close of 1883 at his company's works at Greenville, N. J., these being sufficiently successful to be repeated in November of that year on the Saratoga and Mt. McGregor road. The locomotive used there was called "The Ampere," and pulled a full sized car. The motor was mounted on a platform, and connected by belts to an intermediate shaft carried between the wheels, from which another set of belts lead to pulleys on the driving axles. A center rail and the running rails formed the working conductors. Variation of speed was accomplished by variation of field resistance, this being accentuated by the use of iron instead of copper in some of the coils.

In the following year Daft equipped a small car on one of the piers at a New York seaside resort, and a little later another one at the Mechanic's Fair in Boston, the motor for this last being subsequently put on duty at the New Orleans Exposition. In 1885 work was begun by the Daft Company on the Hampton Branch of the Baltimore Union Passenger Railway Company, where in August of that year operations were begun, at first with two and a year later with two more small electric locomotives which did not carry passengers themselves, but pulled regular street cars. A center and the running rail were used for the normal distribution, but at crossings an overhead conductor was installed, and connection made to it by an arm carried on the car and pressed up against it. The

driving was by a pinion operating on an internal gear on one of the axles.

Daft's most ambitious work followed when a section of the Ninth Avenue Elevated Road was equipped for a distance of 2 miles, on which a series of experiments were carried on during the latter part of 1885, with a locomotive called "The Benjamin Franklin." The motor was mounted on a platform pivoted at one end, and motion was communicated from the armature to the driving wheel through grooved friction gears held in close contact partly by the weight of the machine and partly by an adjustable screw device. This locomotive, pulling a train of cars, made several trips, but the experiments were soon suspended. This work was followed by street railway equipments at Los Angeles and elsewhere, using double overhead wires carrying a trolley carriage.

Meanwhile Bentley and Knight, after some experiments in the yards of the Brush Electric Company at Cleveland in the fall of 1883, installed a conduit system in August, 1884, on the tracks of the East Cleveland Horse Railway Company. The equipped section of the road was 2 miles long, the conduits were of wood laid between the tracks, and two cars were employed which were each equipped with a motor carried under the car body and transmitting power to the axle by wire cables.

These equipments were operated with varying degrees of success during the winter of 1884–85, but were abandoned later. This work was followed by a double overhead trolley road at Woonsocket, the motors being supplied by the Thomson-Houston Company, and later by a combined double trolley and conduit road at Allegheny, Pa.

In 1884, Dr. Wellington Adams of St. Louis proposed a departure in motor mounting which recognized the necessity of removing the motor from the car body and directly gearing it to the axle. In his plan the field magnets were carried by the pedestals, and inclosed the axle on which the armature was to revolve, its motion to be transmitted by gearing. The method was impracticable, and found no application.

In 1884–85, J. C. Henry installed and operated in Kansas City a railway supplied by two overhead conductors on each of which traveled a small trolley connected to the car by a flexible cable. The motor was mounted on a frame supported on the car axle, and the power was transmitted through a clutch and a nest of gears giving five speeds. In the following year a portion of another

road was equipped. A number of experiments seem to have been conducted there, and on some the rails were used as a return. The collectors were of different types, and it is said that among others there was one carried on the car. The final selection was a trolley having four wheels disposed in pairs in a horizontal plane, carried by and gripping the sides of the wires; this feature, but using one wire and rail return, characterized a road installed by Henry in San Diego, Cal., opened in November, 1887.

In the early part of 1885, Sidney H. Short began a series of experiments on a short piece of track in Denver which was followed by the construction, in conjunction with J. W. Nesmith, of a section of road for operation on the series system. These experiments were continued through 1885 and 1886, and were repeated at Columbus, but were doomed to ultimate failure because of the principle involved. Subsequently Short adopted the multiple system of distribution, and for a time essayed the use of gearless motors for tramway work, but reverted later to the geared type.

Meanwhile work had begun in Great Britain, where the first regular road to be put in operation was that known as the Portrush Electric Railway, in Ireland, installed in 1883 by Siemens Brothers of London. Power was generated by turbines, and the current was transmitted by a third rail supported on wooden posts alongside of the track, the running rails constituting the return. The pressure used was about 250 volts.

This was followed in the same year by a successful short road at Brighton, installed by Magnus Volk, the current being transmitted through the running rails. Then came the railway installed at Bessbrook, Newry, in 1885, under the direction of the Messrs. Hopkinson, and at Ryde, in 1886, in which latter year was also installed the Blackpool road by Holroyd Smith. In this latter case the conduit system was used with complete metallic circuit. The motor was carried underneath the car between the axles, and connected by chain gearing. Fixed brushes with end contact were used for both directions of running.

Reverting to work in the United States, Sprague again took up the electric railway problem, and in 1885, before the Society of Arts, Boston, advocated the equipment of the New York Elevated Railway with motors carried on the trucks of the regular cars, and work was actually begun on the construction of experimental motors. Shortly afterward a regular truck was equipped, and a long series of tests made on a private track in New York city. In May,

1886, an elevated car was equipped with these motors, and a series of tests begun on the Thirty-fourth Street branch of the road.

These motors may be considered the parent models of the modern railway motor. They were centered through the brackets on the driving axles, connected to them by single reduction gears, and the free end of the motor was carried by springs from the transom, the truck elliptics being interposed between this support and the car body. The truck had two motors, they were run open, had one set of brushes, and were used not only for propelling the car but for braking it. The motors were at first shunt wound, but later had a correcting coil in series with the armature at right angles to the normal field to prevent shifting of the neutral point. The car was operated from each end by similar switches, current at 600 volts were used, and increase of speed was effected by cutting out resistance in the armature circuit and then by reducing the field strength. This enabled energy to be returned to the line when decreasing from high speed. It being impossible to interest the railway management, the experiments were finally suspended. Soon afterward a locomotive designed by Field had a short trial on the same section of the Elevated.

Sprague then turned his attention to building a locomotive car of 300-hp capacity, each truck to be equipped with two motors, each having a pair of armatures geared to the axle, but this evidently being ahead of the times, and the possibilities of street tramway traction becoming evident, these equipments were abandoned, and he began the development of the type of motor finally used in Richmond, one crude form of which was first used in storage battery experiments in Philadelphia, and others in New York and Boston, in 1886. One of the Elevated motors was put into service at the East Boston Sugar Refinery, and continued so for some-time.

Reviewing the conditions at the beginning of 1887, statistics compiled by Mr. T. Commerford Martin show that, including every kind of equipment, even those a fraction of a mile long and operated in mines, there were but nine installations in Europe, aggregating about 20 miles of track, with a total equipment of 52 motors and motor cars, none operated with the present overhead line or conduit, and seven cars operated by storage batteries, while in the United States there were only ten installations, with an aggregate of less than 40 miles of track and 50 motors and motor cars, operated mostly from overhead lines with traveling trolleys

flexibly connected to the cars. These were partly Daft, but principally Van Depoele roads. Almost every inventor who had taken part in active work was still alive. The roads, however, were limited in character, varied in equipment, and presented nothing sufficient to overcome the prejudices of those interested in transportation, and command the confidence of capital. The whole electric railway art may fairly be termed, and was in fact for sometime afterward, in an experimental condition, and some radical step was necessary to overcome the inertia which existed, and inaugurate that development which has been so remarkable.

This came in the spring of 1887, when the Sprague Electric Railway & Motor Company took contracts for roads at St. Joseph, Mo., and Richmond, Va., the latter covering a road not then built, and including a complete generating station, erection of overhead lines, and the equipment of 40 cars each with two 7 1/2-hp motors, on plans largely new and untried. The price, terms, and guarantees were such as to impose upon the company extreme hazards, both electrical and financial. The history of the Richmond road has been too often written to dwell upon it at any length here. Suffice it to say that after experimental runs in the latter part of 1887 it was put into commercial operation in the beginning of February, 1888, and for a year there followed an experimental period of development which taxed the technical and financial resources of the company to the limit. But it won out, and Richmond, by common consent of history, now stands as that pioneer road which more than any other was effective in the creation of the electric railway as it stands today.

The general features characterizing it may be briefly summarized as follows: A system of distribution by an overhead line carried over the center of the track, reinforced by a continuous main conductor, in turn supplied at central distributing points by feeders from a constant potential plant operated at about 450 volts, with reinforced track return. The current was taken from the overhead line at first by fixed upper pressure contracts, and subsequently by a wheel carried on a pole supported over the center of the car and having free up and down reversible movement, exposed motors, one to each, were centered on the axles, and geared to them at first by single, and then by double reduction gears, the outer ends being spring supported from the car body so that the motors were individually free to follow every variation of axle movement, and yet maintain at all times a yielding touch upon the gears an abso-

lute parallelism. All the weight of the car was available for traction, and the cars could be operated in either direction from either end of the platform. The controlling system was at first by graded resistances affected by variation of the field coils from series to multiple relations, and series-parallel control of armatures by a separate switch. Motors were run in both directions with fixed brushes, at first laminated ones placed at an angle, and later solid metallic ones with radial bearing.

The well-nigh heart-breaking experiences and the alternation of good and bad performances are largely matters of personal history, but the results accomplished soon commanded the attention of those interested in the street transportation, most prominent among whom at that time was Henry M. Whitney, President of the West End Railway of Boston, who was considering the adoption of the cable. He consented to come to Richmond, and accompanied by his associates stopped also at Allegheny City to see the underground conduit of the Bentley-Knight Company. The demonstrations made for his benefit were conclusive, the cable was abandoned, and orders given for trial installations on both the overhead and underground systems to run from the Providence depot in Boston to the suburb of Allston. A winter's run resulted in the abandonment of the conduit and the adoption of the overhead trolley system, the principal orders for equipment going to the Thomson-Houston Company which, having absorbed the Van Depoele Company, was now pushing work energetically. Mr. Whitney's decision had a vital bearing upon the commercial development of electric railways, and from that time there followed a period of extraordinary activity, in which for a time two companies, the Sprague Electric Railway & Motor Company and the Thomson-Houston Electric Company, were the principle competitors. There was a continuous improvement and increase in the size of apparatus. Form wound armatures, proposed by Eickemeyer, replaced irregular windings, and metallic brushes gave way to carbon, this single change, initiated by Van Depoele in 1888–9, going a long way toward making the art a success. Cast and wrought iron yielded to steel, two-pole motors to four-pole, double reduction gears to single, and open motors to closed, protected only by their own casings. In 1892 combined series parallel and resistance control was adopted, when the Thomson magnet blow-out was successfully applied to controllers by Mr. Potter, and this was a most effective agent in reducing the troubles of operation.

The progress of the electric railway, however, was not unimpeded, for no sooner had the Richmond road started than there was emphasized a series of disturbances on the telephone lines which threatened the use of the rails for return, and brought on a conflict with the Bell Telephone Company, far reaching in its character and involving new legal questions. At that time it was almost universal practice for the telephone to be installed with single circuits and earth return. Already the service had become most unsatisfactory because of the multiplicity of electric installations of various kinds, with consequent leakages, troubles from induction and variations in earth potential. To the hissing and frying incident to the system as installed was now added the hum of the motor and exaggerated differences of potential at the ground connections.

The first attempt to meet this was made in Richmond by the superintendent of the exchange, who disconnected from the ground and joined all return wires to a common circuit. This obviated most leakage troubles, but did not get rid of the troubles of induction. Numerous law suits followed in nearly half the States of the Union, the telephone companies attempting to force the railways to use double overhead circuits, and the railway companies demanding their share of the heritage of the earth. The trolley contentions were in the main successful, and individual metallic circuits, vital to successful operation, and without which long distance telephone is impracticable, were adopted, for which condition of affairs the electric railway may be thanked.

The work accomplished at Richmond, the widespread advertising of the equipment and the rapid spread of electric railways in the United States commanded the attention of the Old World, and work was begun in Italy, Germany and elsewhere along the same lines, but it was not until a number of years later that there was any general adoption of the electric railway in the more conservative countries.

Meanwhile the Sprague Electric Railway & Motor Company was absorbed in 1890 by the Edison General Electric, which later combined with the Thomson-Houston Company and others in the General Electric.

For the next six years the record of the electric railway is that of industrial development, practically as indicated in the improvement of apparatus, the replacement of horse and cable power on existing lines, and the creation of new ones. Electric operation

on tramways having become established, there naturally followed more ambitious attempts in limited applications of electricity to heavier work.

In November, 1890, a line on South London road, which was originally designed for cable, was opened, the trains being pulled by electric locomotives equipped with a pair of gearless motors having armatures mounted on the axles of the drivers.

In June, 1891, Sprague offered to install on the New York Elevated road a train to be operated by a locomotive car, and also one with motors distributed under the cars, and to make an express speed of 40 miles an hour. Two years later the Liverpool overhead railway was put in operation. Here the trains were composed of two-car units, each car having one motor, the two being operated by hand control.

In the spring of the same year, 1893, the Intramural Railway was constructed at the World's Fair, the equipment being supplied by the General Electric Company. Four motor cars with hand control were used to pull three trail cars, and a third-rail supply with running-rail return was adopted. Two years later the Metropolitan West Side Elevated road in the same city was equipped on the same general plan except using two motors instead of four.

In May, 1896, the Nantasket Beach road, a branch of the New York & New Haven Railway, was put in operation, and in September the Lake Street Elevated of Chicago began electrical operations. In November of the same year, electric service was instituted on the Brooklyn Bridge, the motor cars being used to handle the trains at first at the terminals but later across the bridge.

There were few attempts, however, to replace steam on regular roads, and only occasionally were electric locomotives adopted for special reasons. Among the earlier ones built were one of 1000 horsepower, 1892–94, designed by Sprague, Duncan and Hutchinson for Mr. Henry Villard for experimental operation on lines out of Chicago, which was never undertaken, and the still larger locomotives built by the General Electric Company, which began operation of the trains in the Baltimore & Ohio tunnel in 1895.

For a long time the conduit system, after its abandonment at Allegheny and Boston, remained quiescent, and all work was practically with the overhead trolley. In 1893 a short line was tried in Washington on the Love system, but it was not until the following year that work was begun in New York on the Lenox Avenue

line, and carried to that successful conclusion which warranted its widespread adoption in that city, under the auspices of Wm. Whitney and Henry Vreeland, and in Washington under Connett, although a line had been in operation at Budapest for some time. All this of course was largely because of the necessary cost of the heavy construction, and because street railway managers would not and could not undertake any such investment except under most favorable traffic conditions, and then with the additional restriction of a prohibition of the use of overhead wires.

About this period there began that rapid introduction of interurban railways, soon aided by the developments in transformers by Stanley, in polyphase transmission by Tesla and Ferraris, and in rotary transformers by Bradley and others, which has had such an influence upon steam railway operation and been so instrumental in knitting together urban and rural communities.

The first practical proposal for a railway using high-tension alternating-current transmission, seems to have been made in 1896 by Bion J. Arnold in plans for a road to run from Chicago to the Lake region, and although this road was never built the general plans were utilized for a line actually put into operation about two years later, which was the forerunner of the standard practice of today by means of which the limitations of distance have been so effectively reduced.

In 1896 Sprague again sought the opportunity to make a demonstration on the Elevated Railway in the form of a proposition to the management to equip a section of the line, and operate a train of cars on a new principle, the "Multiple Unit."

Although the advantages of the system, such as higher schedules, reduced weights, variable train lengths, more frequent trains, distributive motive equipment and increased economy were presented, and supplemented by an offer to equip the whole system, no response whatever was made. A similar proposal repeated seven months later met with like fate, but in the spring of 1897 he made a contract with the South Side Elevated Railroad, in Chicago, to equip the line on this plan in lieu of the locomotive car plan then under consideration.

This system has now become so widely known that any detailed description of it is unnecessary. Generally speaking, however, it is essentially the control of controllers, by means of which cars equipped with motors and controllers for them are operated from

master switches through a secondary line, with provision for so coupling up cars that from any master switch all cars can be operated irrespective of number, order or end relation, or whether all or only part of the cars are equipped with motors.

The first equipment was for 120 cars, and the first public demonstration was made in July, 1887, at Schenectady, on a full train of cars which had been sent from Chicago for that purpose. A regular train was put into operation before the close of the year, and within a few months steam operation was entirely replaced.

As originally equipped, the main controller consisted of a magnet-operated reverser and pilot-motor driven cylinder, operated semi-automatically and with throttle restraint through a secondary line and relays from master switches on the platforms. A number of variations have since been developed, such as operating the reverser and cylinder by air pistons electrically controlled, or breaking the main controller up into several magnetically operated parts, and all forms of equipment are now in operation. The essential principle of the system, however, has not been changed, and it has become standard wherever required to operate electric trains at high schedules. Equipments have grown from 100 horse-power per car to 2200 horse-power per locomotive, for in the largest work under way, that of the New York Central, the locomotives are to be controlled on this plan.

The necessities of tunnel traffic on the one hand and a grave accident on the other have curiously enough centered in New York the largest two electric transportation problems, namely, that of the operation of the Pennsylvania tunnel and terminals, and more extensive still, that of the New York & Hudson River Railroad for 35 miles out from its terminals. The general requirements are so exacting, and the installation of the latter under such difficult continuous working conditions that they will prove of historic interest, and be influential in determining the disposition of many terminal problems.

Up to comparatively recent times most of the electric railways, including those just mentioned, have been planned for operation with continuous current motors at moderate potentials, but this has often required the conversion of alternating current transmitted at high potential into continuous current at a lower one through the medium of transformers and rotary converters. While this bids fair to be the practice for some time, there are of course certain objections which are apparent, and the best energies of many

of the ablest electrical engineers have for some time been bent upon solving the problem of operating directly with alternating currents. Among the most active and successful of these have been the Ganz Company, whose Valtellina line, equipped on the polyphase plan for Italian Government, is of special interest. Among noteworthy experimental installations is that conducted under the auspices of the German Government on the Zossen military line, where the highest record for speed of a car carrying passengers, about 126 miles per hour, has been made during the past year, the current being collected from the three overhead wires by sliding contacts.

The multiplicity of conductors, however, distinctly militates against this as any general solution of the larger railway problems, quite independently of other limitations affecting trunk-line transportation, and hence single-phase operation, using one overhead conductor with track return, is being energetically prosecuted. Among the workers who have sought solution and been active in invention along this line, as well as one of the earliest and most persistent advocates of single-phase railway operation, is Mr. Arnold, who has developed an electro-pneumatic plan in which is combined on a locomotive a constant speed single-phase alternating-current motor with reversible air pumps and a storage tank, by which starting and running can be controlled by compressed air with a more even demand upon the capacity of the station. Arnold's experiments, a long time delayed from various causes, are now being subjected to the actual tests which will demonstrate the practicability of this scheme. Meanwhile, becoming alive to the limitations of past practices and the increasing demands of the art, the engineers of the various manufacturing companies in the United States and Europe, among whom must be especially mentioned Finzi, Lamme, Latour, Winter, Eichberg and Steinmetz, are developing the single-phase alternating-current motor along two general lines. One is by using a series motor of special construction, plain or compensated current being supplied from the secondary of a transformer carried on the car and operated at moderate frequency. Another form is that originally proposed by Thomson, and known as the "repulsion" type, in which the field is supplied directly at high potential, and the armature is short-circuited upon itself and operates at low potential. An alternative of this form is that developed by European engineers, in which a variable potential is delivered to the armature from a transformer, the field being

supplied direct from the line. One desideratum is of course to be able to operate both from alternating and continuous currents, and this has been done, but the best results may possibly be gotten by ignoring this limitation.

It is unnecessary to go into the many variations or details of these various schemes. Suffice it to say that all are being submitted to the crucial test of commercial operation, and the overcoming of difficulties of the early days of electric railroading warrant expectation that a great measure of success will likewise be attained on these new lines, and that another bar to the wider spread of electric railway operation may be speedily removed.

This paper will not be burdened with detail statistics, but to illustrate in a general way the growth of the electric railway it should be noted that three years after the inauguration of the Richmond road there were in operation or under contract in the United States, England, Germany, Italy and Japan, not less than 325 roads, representing an equipment of about 4000 cars and 7000 motors, with 2600 miles of track, on which there was made a daily mileage of not less than 400,000 miles, and three-quarters of a billion of passengers were carried annually.

By the end of 1903, in the United States alone, there was a total of over 29,000 miles equipped, 60,000 motors and 12,000 trail and service cars in service, and the passengers carried ran into billions.

What the electric railway has done may only briefly be referred to here, but the writer may be permitted to repeat the substance of remarks written some nine years ago, for it has become a most potent factor in our modern life, and left its imprint in the indelible stamp of commercial supremacy. It has given us better paved streets, greater cleanliness, more perfect tracks, and luxurious, well-lighted and well-ventilated cars. With the higher speeds it has made possible the extension of the taxable and habitable areas of towns and cities in a much greater ratio than is represented by the increase of speed.

It has released from drudgery tens of thousands of animals, and increased the morale of transportation employees. It has given employment to an army of men, and hundreds of millions of capital. It has improved and extended the telephone service by forcing the abandonment of ground circuits. It has built up communities, shortened the time between home and business, made

neighbors of rural communities, and welded together cities and their suburbs.

Will it replace the steam locomotive?

Perhaps the best answer is that "its future is not in the wholesale destruction of existing great systems. It is in the development of a field of its own, with recognized limitations but of vast possibilities. It will fill that field to the practical exclusion of all other methods of transmitting energy; it will operate all street railway systems, and elevated and underground roads; it will prove a valuable auxiliary to trunk systems; but it has not yet sounded the death-knell of the locomotive any more than the dynamo has that of the stationary steam engine. Each has its own legitimate field."

SOME EARLY WORK IN POLYPHASE AND SINGLE-PHASE ELECTRIC TRACTION.

BY BION J. ARNOLD.

In 1896 I became interested in a proposed road projected to run west and north from Chicago into the lake regions of Wisconsin, and to be known as the Wisconsin Inland Lakes & Chicago Electric Railway.

The rotary converter was then just beginning to be commercially exploited, and had, I believe, been used in some instances for power transmission, but so far as I know it had not been used for railway work. Desiring to construct the road, some 75 miles in length, as economically as practicable, and seeing no reason why rotary converters would not operate on railway work, I decided to adopt a three-phase high-tension transmission system with sub-stations, using rotary converters and storage batteries — a radical departure from the then standard 500-volt direct-current system.

Complete detailed specifications for the road and its equipment were prepared, calling for three-phase generators capable of supplying current at 1040 volts, the necessary step-up and step-down transformers, switchboard apparatus, rotary converters, etc., required to generate alternating-current energy at 1040 volts, transmit it at 5000 volts, and convert it into direct current at 700 volts to supply the overhead conductor, from which standard direct-current railway motors were to be operated, using storage batteries as equalizers in sub-stations distributed along the line.

Fig. 1, which shows the arrangement proposed, is a reproduction of one of the original drawings attached to the specifications submitted to the railway company at the time the final specifications were delivered.

It happened, unfortunately, that the promoters of the road were unable to secure the necessary franchises for its construction, and it remains unbuilt today, while the specifications and plans repose among the archives of my office as evidence that an engineer,

eager to see his ideas executed, is apt sometimes to do much work for no pay and stand the preliminary expenses himself. The territory has since been partially occupied by the Aurora, Elgin & Chicago Electric Railway, and the Chicago & Milwaukee Electric Railroad.

However, while this experience was somewhat disappointing financially, the time and study put upon it were not lost. A few months later the promoters of another road, now a part of the Chicago & Milwaukee Electric Railroad, came and stated that they must build 15 miles of new road in order to connect two small roads, each about a mile long, and that out of the total money

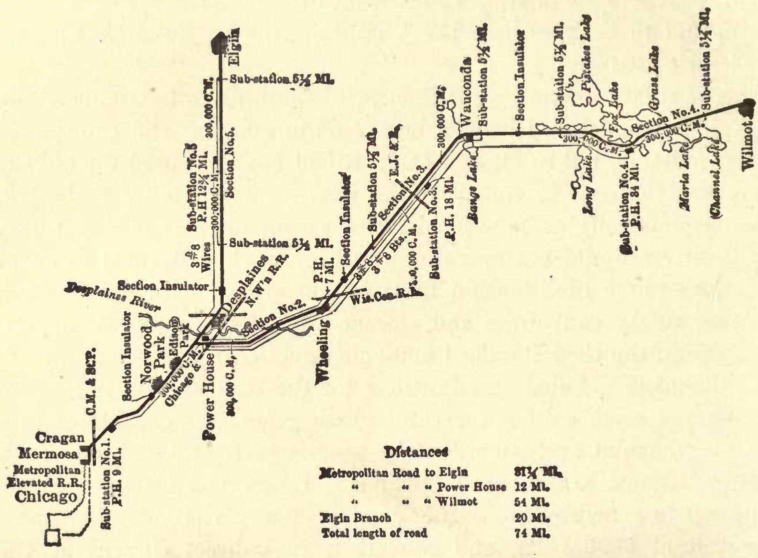


FIG. 1.—MAP SHOWING LOCATION OF POWER-HOUSE, SUBSTATION AND DISTRIBUTION SYSTEM OF THE WISCONSIN INLAND LAKES & CHICAGO ELECTRIC RAILWAY AS PLANNED IN 1896.

available to build this road they had provided but $10,000 to put into copper. After carefully calculating the cost of the road and finding it prohibitive, if built under the then standard 500-volt direct-current system of distribution, the plans of the Inland Lakes Road were resurrected. To have built the new road under the 500-volt direct-current system would have necessitated investing almost as much money for copper alone as the parties had at their disposal for building the complete electrical and mechanical equipment.

After explaining the alternating-current plan and showing its adaptability to the case, and the impossibility of constructing under the standard 500-volt system, a remark was made by one of the owners to the effect that: "If the engineer was willing to take the professional risk the owner would take the financial risk." Authority was secured to build in accordance with the rotary-converter plan I had submitted, on condition that the road must be in operation within 90 days, in order to save the franchises under which it was authorized.

One of the leading manufacturing companies had on hand at this time (March, 1898) three 120-kw rotary converters, which had been built for experimental purposes mainly, and by contracting with this company for the new electrical machinery required for the road, the use of these rotaries, provided with temporary transformers and switchboard apparatus, was secured.

A new power-house was built, a transmission line eight miles long, consisting of three No. 8 bare copper wires carried upon ordinary Western Union single-petticoat glass insulators, was constructed, and the temporary apparatus installed.

It was necessary to belt two of the rotaries in tandem from the fly-wheel of the engine, and use them as generators, one supplying direct current to the section of the line nearest the power-house, while the other supplied three-phase current to the third rotary placed in the sub-station eight miles away. The alternating current was stepped up at the power-house and transmitted at 5000 volts.

The road was opened for traffic July 1, 1898, and ran with fair success with the temporary apparatus until the following spring.

In the meantime the ownership had changed hands, and the new owners, owing to their unfamiliarity with electric railways and the trouble due to the temporary character of the plant (the new machinery not yet having been received from the manufacturers), desired to change the road into a standard direct-current system, and in this position they were supported by several engineers whom they consulted, and who reported adversely to the new system. It was also intended to extend the road southward 10 miles to Evanston, the road previous to this time having extended only from Waukegan to Highland Park, a distance of about 15 miles. In order to prevent the abandonment of my plans and of the alternating system it became necessary for me to assume the entire risk, and a contract was entered into whereby

I undertook to complete and extend the road in accordance with the original designs and guarantee, under a bonus and forfeiture contract, a certain efficiency between the steam-engine cylinders and the car motors under working conditions, and the successful operation of the system as a whole.

The contract was dated March 21, 1899, and as an example of how rapidly engineering and construction work can be done when necessary, I will state that the conditions of the contract were successfully met on time, and when the work called for by it was completed the road stood, on June 20, 1899, equipped with a central power station, and two sub-stations, each eight miles from the

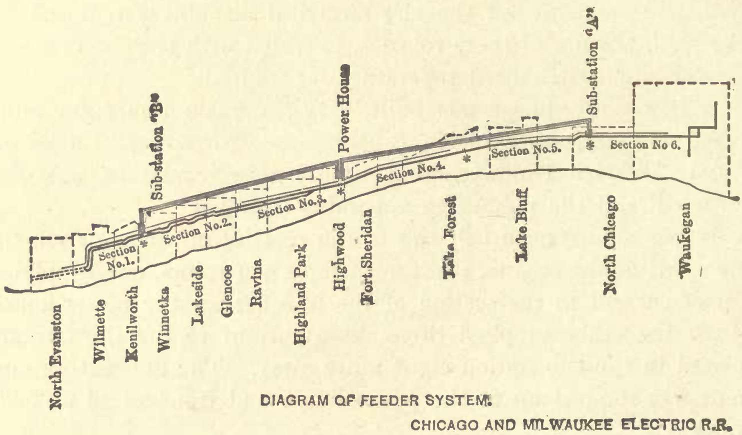


FIG. 2.—MAP SHOWING LOCATION OF POWER-HOUSE, SUB-STATION AND DISTRIBUTION SYSTEM OF THE CHICAGO & MILWAUKEE ELECTRIC RAILWAY COMPANY, AS PLANNED IN 1898 AND COMPLETED IN 1899. FIRST ROTARY CONVERTER SUB-STATION ROAD.

power-house, all equipped with new machinery, regulating batteries, together with all necessary high-tension transmission lines and direct-current feeders for operating 16 40-ton trains between Evanston and Waukegan, a distance of 27 miles, at an average speed of 20 miles per hour, with stops averaging one per mile.

The energy was generated and transmitted at 5500 volts, as this was the highest pressure that the manufacturers, whom the conditions made it desirable to contract with for the electrical machinery on account of their experience and ability to make prompt deliveries, were prepared to furnish machinery for at that time.

The success of the road was immediate, and its traffic has grown so rapidly that its capacity has been increased to three times its original capacity, during the past year, under the direction of my office.

While there was an instance of a one-car road at Concord, N. H., taking its power through a rotary converter, located about four miles from a water-power generating station, the road I describe, I believe, was the first road to be put in operation designed to

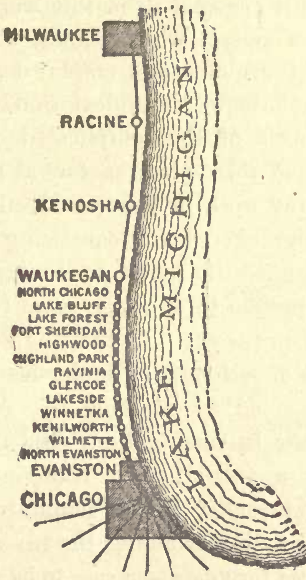


Fig. 3.—Map showing geographical location of the Chicago & Milwaukee Electric Railway.

run from a central alternating-current power station, using high-tension transmission lines, rotary converters and sub-stations.

It was thus probably the prototype of the system that rapidly became standard, and upon which almost all suburban lines have been built since.

Fig. 2 is a map of the road, drawn to scale, giving the relative locations of the power-house and sub-stations, and is a reproduction of one of the original sketches attached to the contract entered into on March 21, 1899. The portion of the line, north of the power-house at Highwood, was installed during the previous year and equipped with the temporary machines.

Fig. 3 shows the relative location of the road to the surrounding territory.

While this system was a marked step in advance in electric railroading, effecting as it did a great reduction in first cost and operation, it did not seem to me to be the final solution of the electric railway problem on account of the losses due to the many conversions of the current and the excessive investment in sub-station machinery, with the attendant operating expenses.

In 1899, while still engaged upon this work, I, therefore, commenced to develop a system which should utilize the alternating current directly in the motor and employ but one overhead conductor, and thus eliminate the sub-station completely, together with the disadvantages of the complicated overhead work made necessary by the use of three-phase motors as then applied to alternating-current railway work in Europe. Realizing the advantages that storage batteries offered for equalizing the load in direct-current work I planned to retain a similar advantage for the alternating-current system by utilizing some form of a storage system to be carried upon the car. As the single-phase motor was not at that time capable of self-starting under load, some supplemental means must be provided for starting it. Air was the medium chosen, for by its use in combination with a high-tension single-phase motor I saw a possibility of requiring not only a single overhead working conductor, but of maintaining a constant load upon the power-house, thus enabling the investment in machinery and transmission lines for any given case to be much less than would be possible with the heavy fluctuating loads common to all electric-railway systems. The essentials decided upon were:

(1) A motor which would use single-phase alternating current without conversion.

(2) Single overhead working conductor.

(3) Steady load upon the power-house.

(4) Independent unit for switching purposes.

The principles underlying the system which I developed to accomplish these results were:

(*a*) A single-phase motor mounted directly upon the car axles, designed for the average power required by the car, running at a constant speed and a constant load, and, therefore, at maximum efficiency.

(*b*) Instead of stopping and starting this motor and dissipating the energy through resistance, as was then common to all railway systems, the speed of the car was controlled by accelerating or retarding the parts usually known as the rotor and the stator, by means of compressed air in such a manner as not only to regulate the speed of the car but also to store the kinetic energy of the car when stopping and utilize it in starting.

Draughtsmen were put at work preparing the Patent Office drawings for different methods of applying the above principles, and late in 1899 an opportunity for trying the system was offered in the case of a road designed to extend about 60 miles northward from Lansing, Mich., and to be known as the Lansing, St. Johns & St. Louis Electric Railway. In January, 1900, I rode over the proposed right of way with a party of gentlemen interested in the road, and as a result of the negotiations that ensued a contract for its

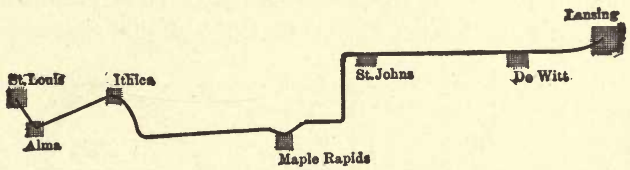


Fig. 4.—Map showing location of the Lansing, St. Johns & St. Louis Electric Railway. First single-phase road.

construction was entered into on April 23, 1900, wherein I undertook to build the road, assuming part of the financial risk.

Fig. 4 is a reproduction of one of the original sketches attached to the contract, and Fig. 5 is a map showing the relative location of this road to the other roads in the State of Michigan.

Locating engineers were at once placed in the field, and the construction proceeded systematically until 20 miles of the road (extending from Lansing to St. Johns) were completed to such an extent that it was opened for operation with steam locomotives about Nov. 15, 1901.

For financial reasons the construction work was delayed but in the meantime the development of the electrical system was going on in different offices and shops.

The overhead work of the 20-mile section of the road was completed and ready for operation about Dec. 15, 1902, and the power installed, so that experiments with the electropneumatic system began in March, 1903. During these and all subsequent experi-

ments the power was supplied from a 300-kw rotary converter, generating at 25 cycles and located in a combined water and steam-

Fig. 5.—Map showing relative geographical location of the Lansing, St. Johns & St. Louis road.

power plant about two miles from the Lansing end of the line. The energy was carried to the motor over two No. 3 bare copper

wires, one of which was attached to the rails of the track and the other to the No. .00 trolley wire. Much experimental work had been done at the shops where the machine was constructed during the preceding year.

On June 15, 1903, two trips were made, each about three miles long, with the first experimental machine, which is illustrated in Fig. 6.

On the first trip eight persons[1] were carried and on the second trip 13[2] persons were aboard, and I give the names, as I believe this was the first public demonstration of a single-phase railway built for commercial use. At this time the voltage on the overhead conductor was carried at 2400 volts.

The locomotive was a crude affair made hastily from a truck of one of the cars (Fig. 7) upon which was placed the motor, some rough timber for supporting the transformers, and the air tanks and controlling devices originally planned to be placed on a large car as shown in Figs. 8 and 9, but which a single motor was unable

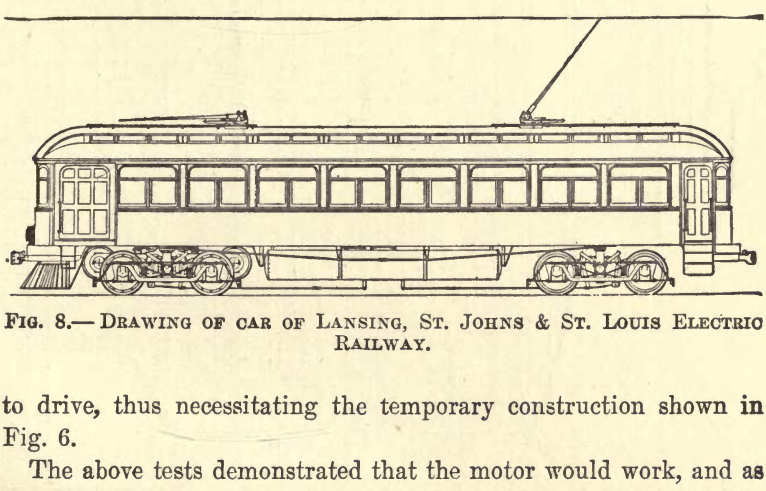


FIG. 8.— DRAWING OF CAR OF LANSING, ST. JOHNS & ST. LOUIS ELECTRIC RAILWAY.

to drive, thus necessitating the temporary construction shown in Fig. 6.

The above tests demonstrated that the motor would work, and as the first machine was necessarily a makeshift and had been considerably damaged during its preliminary trials, it was thought best not to attempt further tests until a complete equipment could be built.

1. A. S. Courtright, G. A. Damon, W. A. Blanck, J. F. Scott, T. M. Keeley, Fred Rider, M. P. Otis and B. J. Arnold.

2. Mr. and Mrs. A. S. Courtright, Paul Courtright, Mr. and Mrs. T. M. Keeley, Leroy Keeley, Mr. and Mrs. Fred Rider, Mrs. T. E. Hamilton, Mrs. A. N. Hamilton, Miss Isabel Hamilton, H. B. Quick and M. P. Otis.

A new double-motor equipment in the form of a locomotive, illustrated in Figs. 10 and 11, was completed and made ready

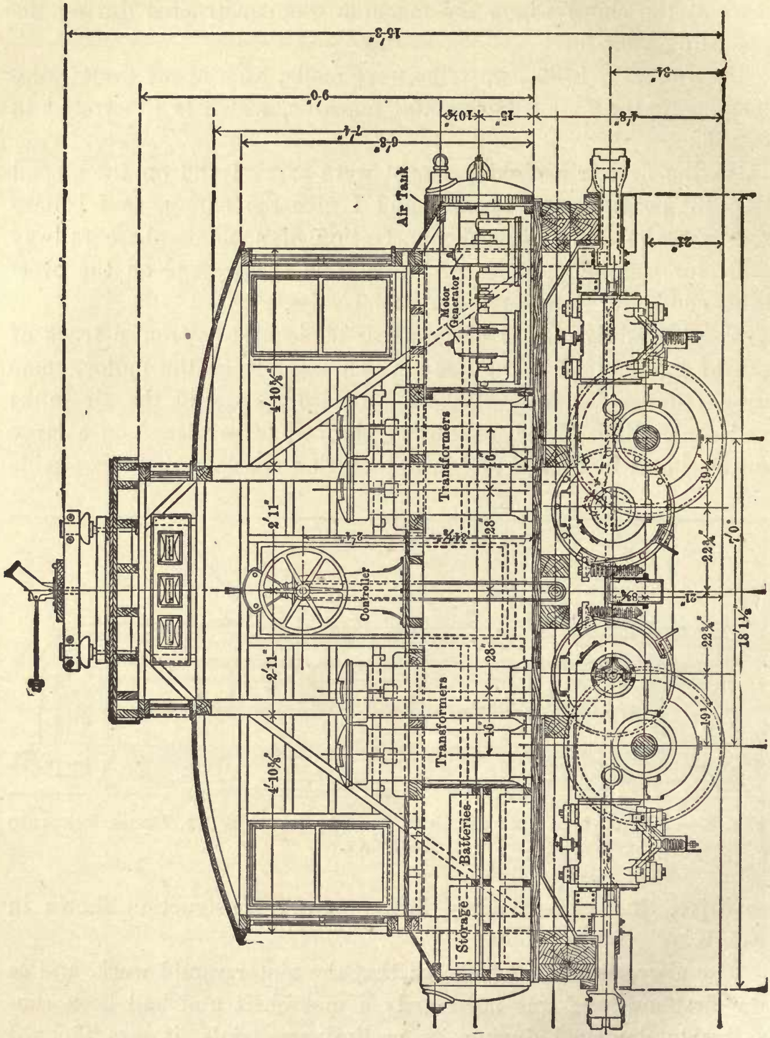


Fig. 10.—Longitudinal section of locomotive no. 2.

for operation early in December, 1903, but on the morning of Dec. 18, a few days prior to the date set for public tests, the carhouse in which it was stored was completely destroyed by fire

and with it went the locomotive, two new cars built for the system, and a steam locomotive used on the line.

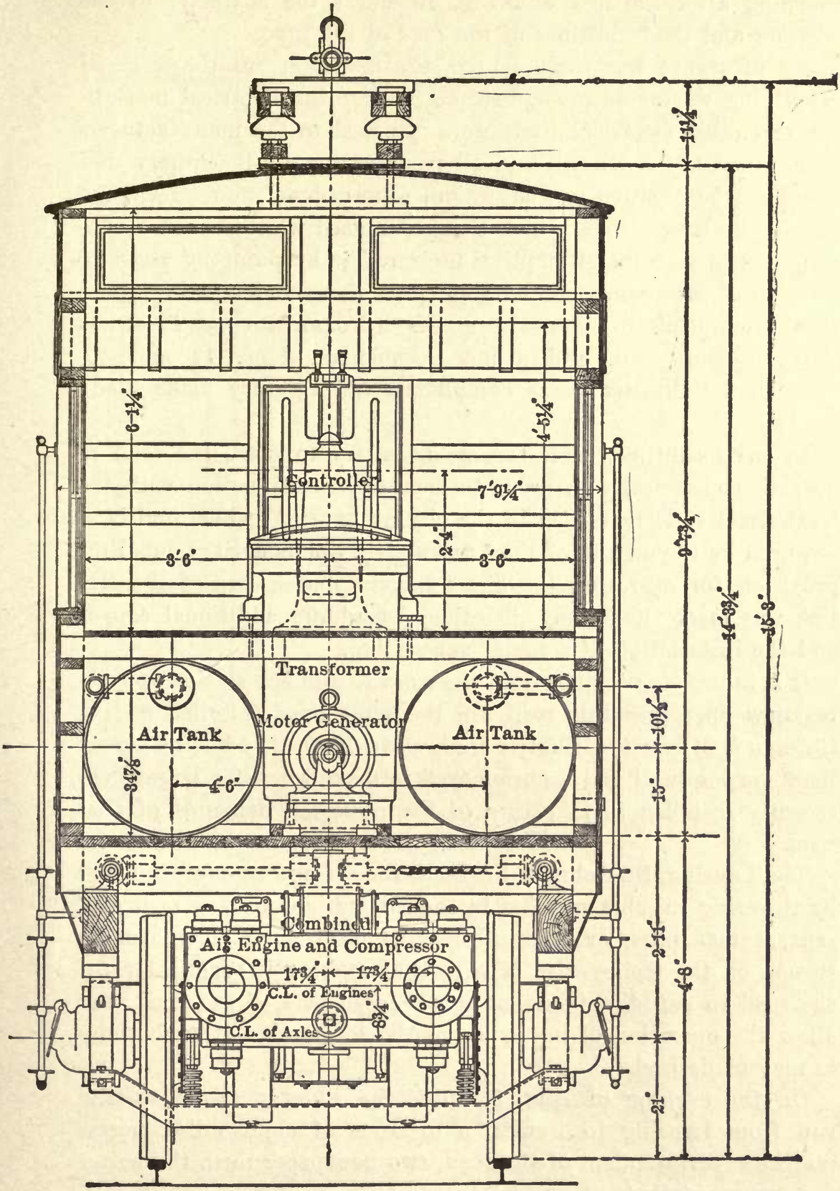


FIG. 11.— TRANSVERSE SECTION OF LOCOMOTIVE NO. 2.

Unfortunately no photographs were secured of the complete machine before it was destroyed, but Fig. 12 shows the wreck the morning after the fire, and Fig. 13 shows the character of the weather and the conditions of the road at the time.

No insurance was carried upon the machine, but the work of rebuilding was at once commenced. All of the electrical machinery and other electrical parts were returned to the manufacturers to be rewound or rebuilt, and all parts of the air machinery that could not be repaired on the ground were ordered new, except the main cylinder castings, which though cracked were in such a condition as to warrant attempting their repair by pumping a strong solution of sal ammoniac and water into them under pressure and thus attempting to close the cracks by oxidization. This was partially successful, and a new locomotive, Figs. 14 and 15, christened "Phœnix" was completely and recently made ready for trial.

In the meantime, as it became necessary to place the road in operation electrically in order to operate in conjunction with the local street railway system in the city of Lansing, which had been acquired by the owners of the Lansing, St. Johns & St. Louis line, provision for operating the direct-current motor cars of the city line was made, under my direction, by adding additional copper and the installation of a rotary sub-station.

It is interesting to know that the rotaries and sub-station apparatus now operating this road are the same ones installed on the Chicago & Milwaukee Electric Railway in 1899, they having served their purpose well and been removed to make room for larger ones recently installed to take care of the increased demands of that road.

The Lansing, St. Johns & St. Louis road is now so equipped that by throwing suitable switches in the sub-station, either direct current at 600 volts, or alternating current at 6000 volts, can be turned on the trolley-wire at will, thus making it practicable for the road to run direct-current cars a large part of the time, and allow the operation of my experimental locomotive at such times as may be desired.

On the evening of Aug. 3, 1904, the Phœnix made its trial run from Lansing to Dewitt, a distance of eight miles, carrying the superintendent of the road, two newspaper men, the writer and three assistants.

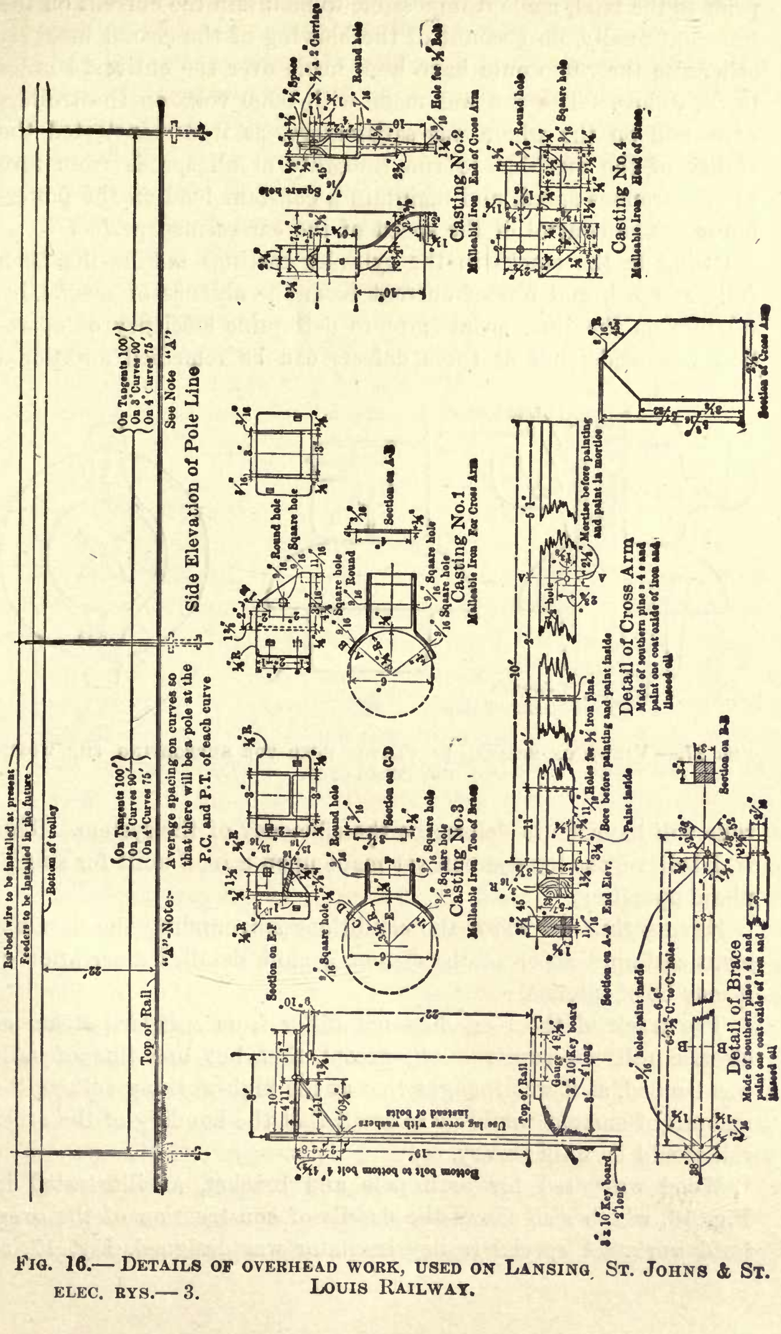


FIG. 16.— DETAILS OF OVERHEAD WORK, USED ON LANSING, ST. JOHNS & ST. LOUIS RAILWAY.

Trouble in the power-house, due to the breaking of an engine prior to the trial, made it impossible to maintain the current on the line continually, on account of the blowing of the circuit breaker; otherwise the run would have been made over the entire 20 miles to St. Johns. The run was made with 6000 volts on the trolley-wire, and on the whole was satisfactory, as it demonstrated the ability of the machine to run smoothly at all speeds from zero to synchronous speed, and maintain a constant load on the power-house. The control of the speed of the car seemed perfect.

Owing to the cracks in the cylinder castings not having been fully stopped, and loss of current from the absence of several insulators on the line, no attempt to determine efficiency of operation was made, but as these defects can be remedied additional

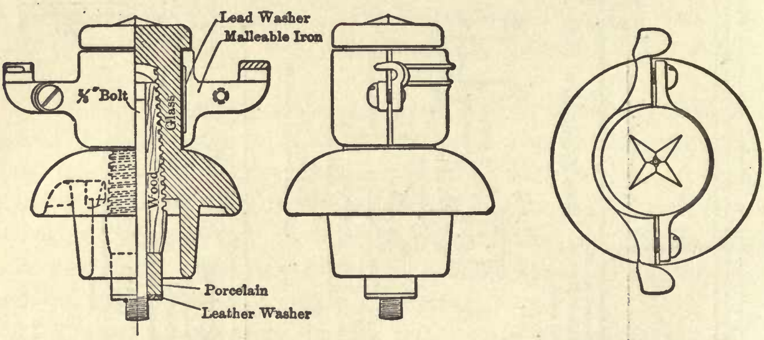


FIG. 17.—VIEWS OF SPECIAL INSULATOR USED FOR SUPPORTING THE WORKING CONDUCTOR.

runs will be made to determine the efficiency of the system. This is, I believe, the longest run yet made upon a road built for single-phase operation.

Having thus described the conditions surrounding the development and application of the system, a more detailed description of it may be of interest.

The track of the road does not differ from standard steam or electric railroad construction, except that but one line of rails was bonded, as it was thought that at the high-working voltage the amount of current would be so small that the bonding of the other rail would be unnecessary.

Wood was used for both pole and bracket, as illustrated in Fig. 16, which also shows the details of construction of the overhead work. A special trolley insulator was designed, Fig. 17, as

it was intended to experiment with pressures as high as 15,000 volts on the working conductor. The insulators were made of annealed glass and tested up to 30,000 volts.

Had a bow or some form of sliding contact been used as originally intended, these insulators would probably have proven satisfactory; but with the running of short four-wheeled direct-current cars over the line came the frequent jumping off of the trolley wheels, resulting in the breaking of many of the insulators. Such construction should, therefore, not be used with anything but a sliding contact or bow trolley.

One of the most difficult problems in the development of the electropneumatic system was to design an air compressor which would not only work efficiently as a compressor but could also be made to work efficiently as an engine. Much time was spent upon the development of various valve mechanisms and many types of engines were designed. The objects to attain were first, quick-opening and quick-closing valves; and second, valves so driven that when the machine was not running as an engine they would not be mechanically moved. They should also be capable of operating automatically when the machine is running as a compressor. By the development of electropneumatically operated valves. described later, these objects were accomplished, and the inequality of the point of cut-off, due to what is technically known as "the angularity of the connecting rod" was eliminated, thus making it possible for each compressor when running as an engine to open its inlet and outlet valves at exactly the right point of cut-off for each end of the cylinder under all conditions of operation, regardless of the direction in which the engine runs. This was accomplished by the use of valves which operate pneumatically without loss of air, the time of opening and closing being electrically piloted by means of collector rings mounted upon or driven by the main shaft of the engine. These collector rings consist of several insulated segments so placed with reference to the crank that they operate the valves instantaneously at such times as an eccentric would if it were placed directly in line with or directly opposite the crank pin.

Primarily a car-motor equipment consists of a single-phase motor having both its rotor and its stator free to revolve (Figs. 18 and 19), each of which is attached to an air compressor in such a manner that when it revolves its compressor will be driven or either air compressors may at times become an air engine and drive the part

of the electric motor to which it is attached. Fig. 20 shows the bottom view and Fig. 21 the top view of the combined electro-pneumatic motor standing on end in the shop prior to being placed upon the truck, and Figs. 22 and 23 show the two motors complete mounted upon a truck. The following description will make clear the application of the principles and the operation of the different parts of the system. Perhaps I cannot describe the theory and working of the machine better than by employing language which I have previously used, so amplified as to conform to the additional figures given in this paper showing more clearly the interior mechanism of the machine.

Fig. 24 represents diagrammatically the working parts of the

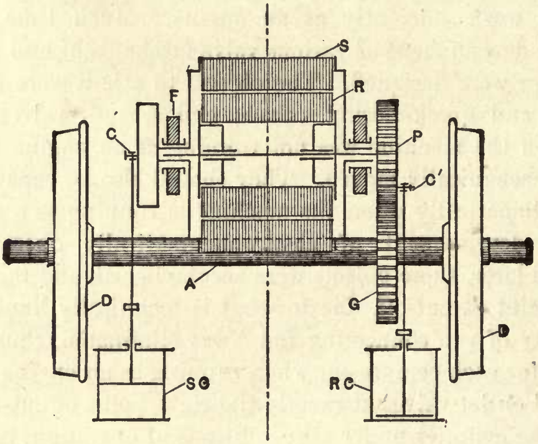


FIG. 24.—DIAGRAMMATIC ARRANGEMENT OF ELECTRO-PNEUMATIC MOTOR.

system when a reciprocating type of air compressor is used. Fig. 25 shows a transverse section through the air cylinders, the regulating valves and the individual cylinder valves of the machine shown in Figs. 22 and 23.

The rotor *R,* Fig. 24, is geared to the axle of the car, and by means of crank pin *C′*, secured in pinion *P,* also drives the compressor cylinder *R C,* while the stator *S* is free to revolve around the rotor and drive by means of crank-pin *C* the compressor cylinder *S C.* Both cylinders are piped to air reservoirs located under the car, and are also provided with suitable valves, *A, B, C* and *C′*, shown in Fig. 25, which in connection with the pneumatically operated cylinder valves previously mentioned, are manipulated

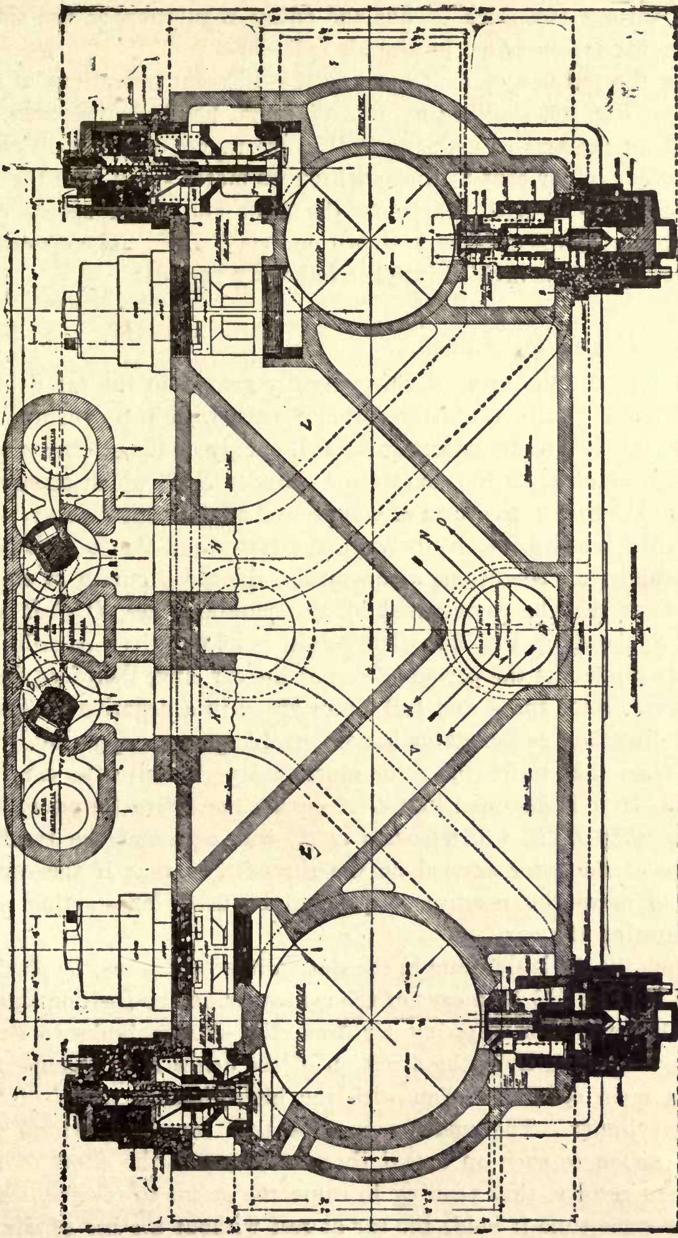


FIG. 25.—TRANSVERSE SECTION THROUGH CYLINDERS AND VALVES OF LOCOMOTIVES 2 AND 3.

from the controller in such a manner as to make them perform their various functions. Thus the entire regulation of the speed of the car is controlled by the air cylinders.

For the purpose of making clear the different operations of the system, Fig. 26, showing a speed diagram, has been prepared, in which on the axis of abscissæ *O D L* are represented the different car speeds in per cent of the synchronous motor speed, and the co-ordinate axis *A O B* represents the rotor and stator speeds corresponding to the car speeds shown on axis *O D L*. The operation of the car may be divided into the following periods:

1. *Standing in the Station.*

In Fig. 24, the rotor *R* being rigidly geared to the car axle is now standing still, while the stator *S* runs with full synchronous speed, and is thus transferring the full energy of the electric motor through crank *C* to the compresser cylinder *S C*, which energy is being delivered in the form of compressed air into the air reservoir. Since the relative velocity between the stator and the rotor is constant under all conditions of operation, the speed curves of stator and rotor may be represented by two parallel lines, *O C R* and *A D S*, shown in Fig. 26. The origin *O* of the given co-ordinate system represents the period of rest of the car, and, therefore, indicates zero rotor speed and full stator speed in a negative or downward direction, as the stator is now revolving in an opposite direction from that which the rotor must revolve to drive the car forward. If it is assumed that *O A* equals the active torque of the stator, then *O B*, which equals *O A*, will represent the reactive torque of the rotor exerted on the car axle, so that if the car is free to move the reactive torque can be used for starting and accelerating the car.

When the car is standing in the station it is held at rest by placing valve *B* (Fig. 25) by means of the controller, in the position shown in full lines, thus allowing air from the storage tanks to enter through opening *Q* in the direction of the arrow *R* to passage *H'*, which is in communication with the high-pressure valves of the rotor cylinder. The pressure may be thus increased behind the rotor piston to such an extent that it overcomes the effort of the rotor to revolve, thus tending to cause the stator to revolve, while at the same time it holds the car at rest without the use of wheel-brakes. When the car is standing, the stator is running at full

synchronous speed and the stator cylinder is drawing in cold air through opening *D* in the direction of arrow *O,* which enters the stator cylinder through the inlet valves shown at the top of the cylinder. The air is delivered from the stator cylinder through the outlet valves into passage *H,* and may be delivered in the direction of arrow *R* into opening *Q* and thence to the storage tanks or into the passage *H'* for the purpose of holding the rotor cylinder still or supplying it with air in starting.

2 *Starting and Accelerating.*

To start the car the air cushion behind the piston of rotor cylinder *R C,* Fig. 24, is removed by so manipulating the controller that the exhaust valves shown at the top of Fig. 25 are opened;

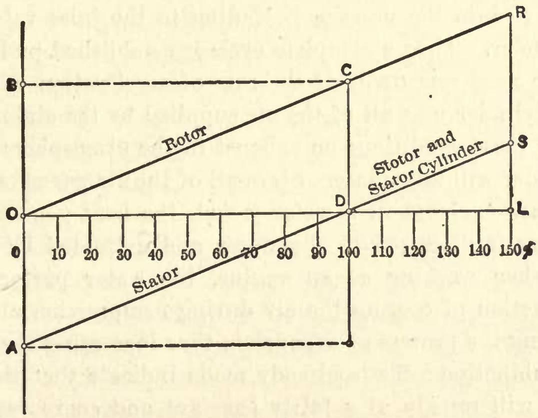


FIG. 26.—DIAGRAMMATIC REPRESENTATION OF OPERATION OF ELECTRO-PNEUMATIC MOTOR.

the air which is being compressed by the stator cylinder is then delivered from passage *H* into *H',* as indicated by the arrow *R,* supplemented by the stored air from the tanks. The controller is now set at the position of maximum cut-off for the inlet valves of the rotor cylinder, shown at the bottom of Fig. 25.

The rotor then begins to revolve and as it accelerates the stator slows down by exactly the same amount that the rotor has increased its speed; as the rotor and car speed increase the controller is gradually moved so that the inlet valves of the rotor cylinder give a smaller percentage of cut-off until the car speed corresponds to the full synchronous speed of the motor, at which time the stator

comes to rest. During this period of acceleration the air compressed by the stator cylinder, instead of being delivered to the tanks to lose its heat, is delivered, hot, directly to the rotor cylinder through the passages H and H', either directly, as indicated by arrow R, in case the valve A is placed as shown in full lines, or through the automatic valve C, as indicated by arrow S, thence through a passage (not shown) communicating with opening Q. In the latter case the valve A is placed in position A'. The valve C, known as the stator automatic valve, is provided with a spring so set that it maintains a constant pressure in passage H and hence a constant load upon the electric motor.

After the air thus delivered from the stator cylinder has done its work behind the rotor piston, it is exhausted cold, owing to the rapid expansion, into the passage L', and thence in the direction of the arrow N into the passage L leading to the inlet valves of the stator cylinder. Thus a complete cycle is established and the same air may be used repeatedly if the rate of acceleration is such that the rotor cylinder uses all of the air supplied by the stator cylinder and under these conditions no exhaust to the atmosphere from the rotor cylinder will take place. Since all of the air passages and both cylinders are enclosed in a water-jacket, the heat generated while compressing is delivered to the water and extracted by the rotor cylinder when working as an engine, the water performing the double function of cooling the air during compression and reheating it during the process of expansion, thus increasing the efficiency of the combination. Tests already made indicate that this jacketing water will remain at a fairly constant and comparatively low temperature.

Opening D is known as the cold-air inlet and the exhaust outlet. It is provided with a valve acting against a spring which normally keeps opening D closed to the outside air. In case the volume of air required by the stator cylinder is greater than the amount exhausted from the rotor cylinder, this valve automatically opens and permits the outside air to enter the passage L through the opening D, as indicated by the arrow O. This valve also opens automatically to admit air to the rotor cylinder in the direction of the arrow P at such times, hereinafter described, as it may be compressing air. The valve is also electrically controlled in such a manner that it can be opened by the motorman when it is desired to operate the car as an independent unit with air alone by means of the rotor cylinders acting as engines.

Referring to Fig. 26, which graphically represents the period of acceleration, since the electric motor always runs at a constant speed and constant load, it has a constant torque, and, therefore, the vertical distance $O\ A$ between $A\ D\ S$ and $O\ C\ R$ may be considered as representing the energy delivered by the electric motor. The length of any ordinate extending from $O\ D$ to $O\ C$ represents the proportionate amount of energy derived from the electric motor which is applied directly through pinion P and gear G, Fig. 24, to the propulsion of the car wheel. The corresponding ordinate extending below $O\ D$ to $S\ D$ represents the proportionate amount of the energy of the electric motor which is absorbed in compressing air through the cylinder $S\ C$, which energy, in the form of air, is immediately transferred to cylinder, the $R\ C$, and is utilized in accelerating the car. In practice, however, since there will be some loss in transferring the energy from electrical energy to energy in the form of compressed air and back again into mechanical energy, the energy thus lost, whatever it may be, must be drawn from the storage tanks and the requisite amount of air from these tanks supplied to the rotor cylinder $R\ C$ in order to maintain the full power of the electric motor upon the car axle during the period of acceleration.

Should it be desired to accelerate at a greater rate than the full power the electric motor is capable of giving to the car, the additional energy may be supplied in the form of air from the storage tanks through the rotor cylinder, thus increasing the total energy given to the car during acceleration, in which case this total power would be represented for any given instant by a point above line $B\ C$.

The air thus drawn from the tanks enters through the opening Q and flows in the direction of arrow R into the passage H', and thence to the rotor cylinder.

3 *Running Speeds.*

Assuming that during the accelerating period valve A has been in position A', the air from the stator cylinder has been delivered through the stator automatic C, and a constant load has been maintained upon the motor. As soon as the car by the previous processes reached a speed corresponding to the synchronous speed of the motor, the exhaust valves of rotor cylinder $R\ C$ are held open by setting the controller at a suitable position and the piston of the rotor cylinder now runs free. The electric motor now gives its

full power to the car axle and the stator and its air mechanism remain at rest as long as the car runs at the speed corresponding to the synchronous speed of the motor. Since the pressure behind the piston of the stator cylinder is maintained constant by the valve *C*, the stator will remain at rest only so long as the resistance offered by the car is exactly equal to the power of the electric motor. In case this resistance is less than the capacity of the electric motor, the stator cylinder will automatically reverse and begin to rotate in the same direction as the rotor is running, and slowly compress air and deliver it to the storage reservoir. In case the resistance of the car is greater than the capacity of the motor, the speed will decrease and the stator automatically reverse and run in an opposite direction from that of the rotor, and will then be operating in the same manner as during the accelerating period. It will thus be seen that no attention need be paid to the stator during the running period, for it automatically takes care of itself.

When the resistance of the car is greater than the capacity of the electric motor, speeds above synchronism can be maintained only by supplying the rotor cylinders with stored air from the tanks, and can only be maintained for short distances, or until the storage capacity of the air reservoirs is exhausted.

The distance from the line *O D L* to that portion of the line *A D S* above *O D L* in Fig. 26 represents, at any given speed, the proportionate amount of energy which must come from the tanks and be supplied through cylinder *S C*. The distance from *D L* to *C R* represents the total energy given to the car by the combined action of the electric motor and stator cylinder.

4 *Retardation.*

To bring the car to rest, instead of applying mechanical brakes to the wheels in the ordinary manner, thereby dissipating the entire stored energy of the car in the form of heat, this energy is saved in the form of compressed air to assist in starting the car, by setting the controller in such a position that the rotor cylinder compresses air and delivers it into the storage tanks. Any desired rate of retardation can be secured by throttling the delivery passages from the rotor cylinder by means of valve *B*, Fig. 25, by moving it toward the direction indicated at *B′*. When the valve is in the position *B′*, the passage *H′* is brought into communication with the automatic valve *C′*, so set that it will release just before the slipping point of the wheels is reached. The kinetic energy of the

car can thus be all absorbed by means of the rotor cylinder and the car brought to rest without wheel brakes, although such brakes are supplied for emergency, but need not be often used.

5. *Reversing.*

When it is desired to run the car backward for short distances the electric motor is not disturbed, and the power is furnished from the rotor cylinders acting as engines; but if it is desired to run backward for any great distance, the current is thrown off the motor, the stator engine is reversed and the stator is brought to speed with the air, when the current is again thrown on to the motor, and the cycle of operation is the same as when running forward.

A detailed description of the valves may now be of interest:

Description of Valves.

Referring to Fig. 25, the lower valves are termed the high-pressure valves and act as inlet valves when the machine is running as an engine and as outlet valves when the machine is running as a compressor.

The upper valves are the outlet or exhaust valves when the machine is running as an engine and the inlet or admission valves when the machine is running as a compressor. Both valves are shown in detail drawn to a larger scale in Fig. 27.

In Fig. 27 (bottom valve) part 15–79 is the valve proper and is of steel; it is carried in a brass guiding case, 15–464, screwed solidly in the retaining walls of the cylinder. Into this seat 15–464, is screwed a brass guiding piece, 15–463, which serves the double purpose of guiding the solenoid plunger, 15–78, and as a chamber for the solenoid coil *X*. In the center of the valve 15–479 is bored a round, true socket or port chamber, into which fits a round plunger or piston, this being an integral part of the solenoid core, 15–78. This core carries a flange, also integral with it, against which the spring 15–80 rests, the other end of the spring resting against 15–463. Surrounding the solenoid core 15–78, is placed a solenoid coil *X* which, when energized, draws 15–78 downward and with it the piston which fits into the port chamber, 15–79.

Valve 15–79 is provided with one or more ports, *a*, drilled into its face and terminating in the central port chamber. It is also provided with radial ports, *b*, terminating in the port chamber. The portion of the solenoid core, 15–78, which enters the port chamber is also provided with channels, *c*, drilled longitudinally,

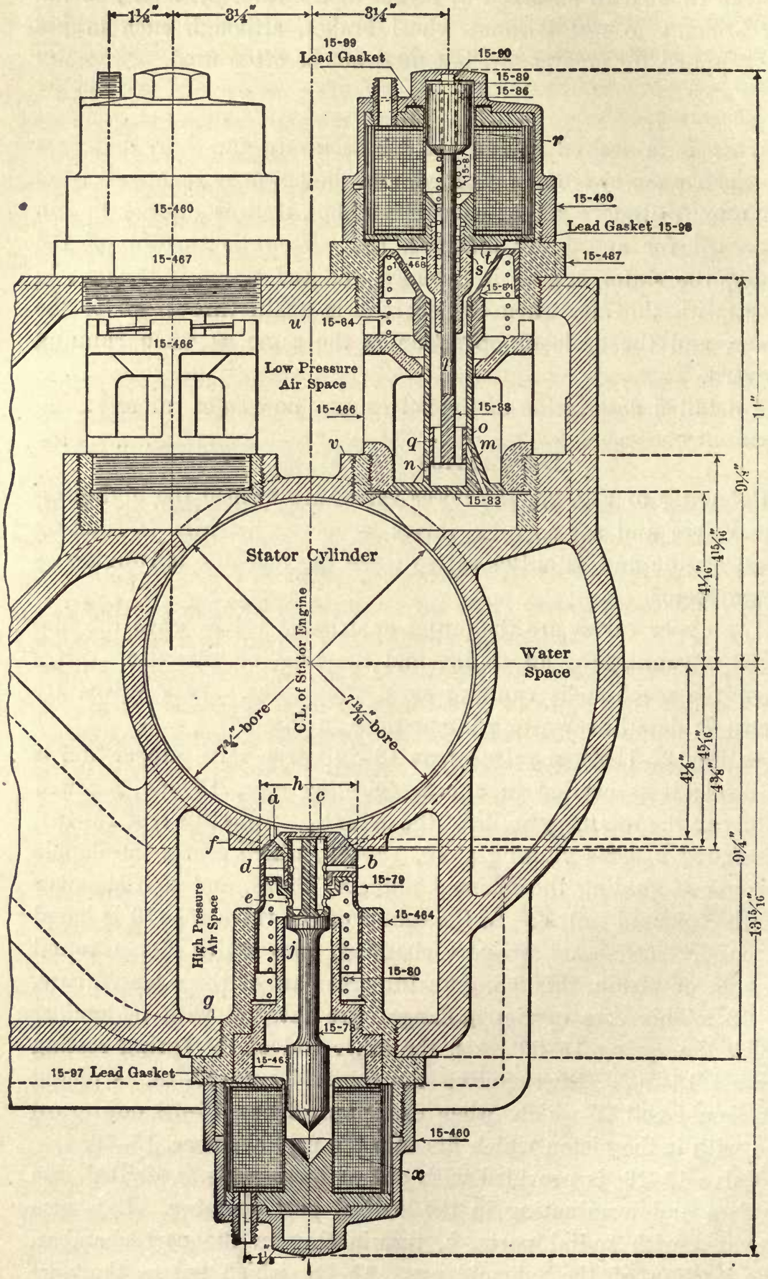


FIG. 27.—SECTION OF CYLINDER THROUGH VALVES.

which are connected with radial openings *d* and *e*. Under normal conditions of operation the space between walls *f* and *g* is filled with air.

Valve 15–78 is round, and the portion *h* is slightly less in diameter than portion *j*, the latter sliding air tight in 15–464, so that if pressure is admitted through ports *b*, *d*, *c* and *e*, into the chamber behind 15–79, the pressure will act upon the portion *j* of the piston or that portion which has the largest diameter and consequently the greatest area, and the valve will be held tight against its seat. The operation of the valve is then as follows:

When working as an admission valve for the engine, current is sent through the solenoid coil *X*, which causes the solenoid core 15–78 to be pulled downward, thus withdrawing its upper portion which fits into the port chamber, causing port *a*, normally closed by 15–78, to be opened, thus allowing the air to flow from the interior of portion *j* out through ports *e*, *c* and *a* into the cylinder. While this air is thus permitted to escape into a larger opening, it is not lost for it must act upon the piston before escaping to the atmosphere. Since portion *h* is smaller in diameter, and, therefore, of less area than *j*, the high-pressure air surrounding the valve will force 15–79 downward, thus opening the main port previously closed by 15–79, allowing the high-pressure air to flow from the high-pressure air chamber into the cylinder. Port 15–79 will remain open as long as current is held upon the solenoid coil *X*; but as soon as current is turned off from the solenoid coil, spring 15–80 forces 15–78 upward, thus closing port *a*, and allowing air to again enter through ports, *b*, *d*, *c* and *e* into the chamber behind 15–79, which forces it upward to its seat on account of the larger diameter and consequently larger area of portion *j*. By sending current through the solenoid coil at suitable intervals by means of the collector rings previously referred to, the valve can be made to open and close and act as an admission valve when the machine is operating as an engine, using air for its driving power and utilizing the air to be used in the cylinder of the engine afterward. The solenoid feature of the valve, therefore, acts only as a pilot and requires but little energy, which can be supplied from the line or from any secondary source, such as a small motor-generator or a storage battery.

When acting as an outlet valve for the compressor, no current is sent through the solenoid coil, and 15–78 is held in its upward position by the spring 15–80, thus, as before, admitting high-pres-

sure air through ports *b, d, o* and *e,* behind portion *j* of 15–79, the air thus supplementing spring 15–80 to hold 15–79 against its seat. The valve will thus operate automatically like the outlet valve of an ordinary air compressor whenever the pressure in the cylinder is sufficiently great to overcome the combined action of spring 15–80 and the air pressure behind 15–79.

Referring now to the upper or low pressure valve, Fig. 27, part 15–466 is a brass seat normally screwed into the casting of the cylinder. In the drawing these valves on the stator cylinder are shown screwed at their bases into brass bushes which have nothing to do with the valves, but were used on the stator side on account of a mechanical defect in the stator cylinder casting.

As in the case of the high-pressure valves, part 15–467 is a brass seat screwed into the cylinder casting, and screwed on it for mechanical protection of the solenoid coil is a cast-iron part 15–460. On the interior of 15–467 fits piston 15–81, which is screwed on to valve seat 15–83, thus making parts 15–81 and 15–83 practically integral so far as operation is concerned, they having been made in different parts only for convenience in assembling.

Part 15–83 is provided with a round port chamber into which ports *m* and *n* enter in such a manner that they can be closed or opened by plunger *o.* Plunger *o* is made of steel and is firmly secured to plunger rod *p* and provided with ports *q* extending completely through it. To the upper portion of rod *p* is attached the solenoid core *r.* Solenoid *r* and with it rod *p* and plunger *o* are normally held in their upward position by means of spring 15–87 resting against part *s* which is screwed into part *t,* the latter forming the path for the lower part of the magnetic circuit created by the solenoid coil. The chamber between walls *u* and *v* is the exhaust or low-pressure chamber. The action of the valve when in operation as an exhaust valve when the stator cylinder is operating as an engine is as follows:

Spring 15–87 normally holds plunger *r* and with it rod *p* and plunger *o* in their upward position, thus causing plunger *o* to close the ports *m.* When it is desired to operate the valve, and thus exhaust air from the cylinder, current is sent through the solenoid coil, which causes plunger *r* to be drawn into the solenoid coil and downward against the resistance of the spring 15–87, thus carrying the stem *p* and plunger *o* to the downward position and opening the ports *m* so that the air behind the piston of the stator cylinder can flow freely through ports *m* up through the interior

of the port chamber inside of 15–83 and enter the space above piston 15–81. As the piston 15–81 is larger in area than the valve

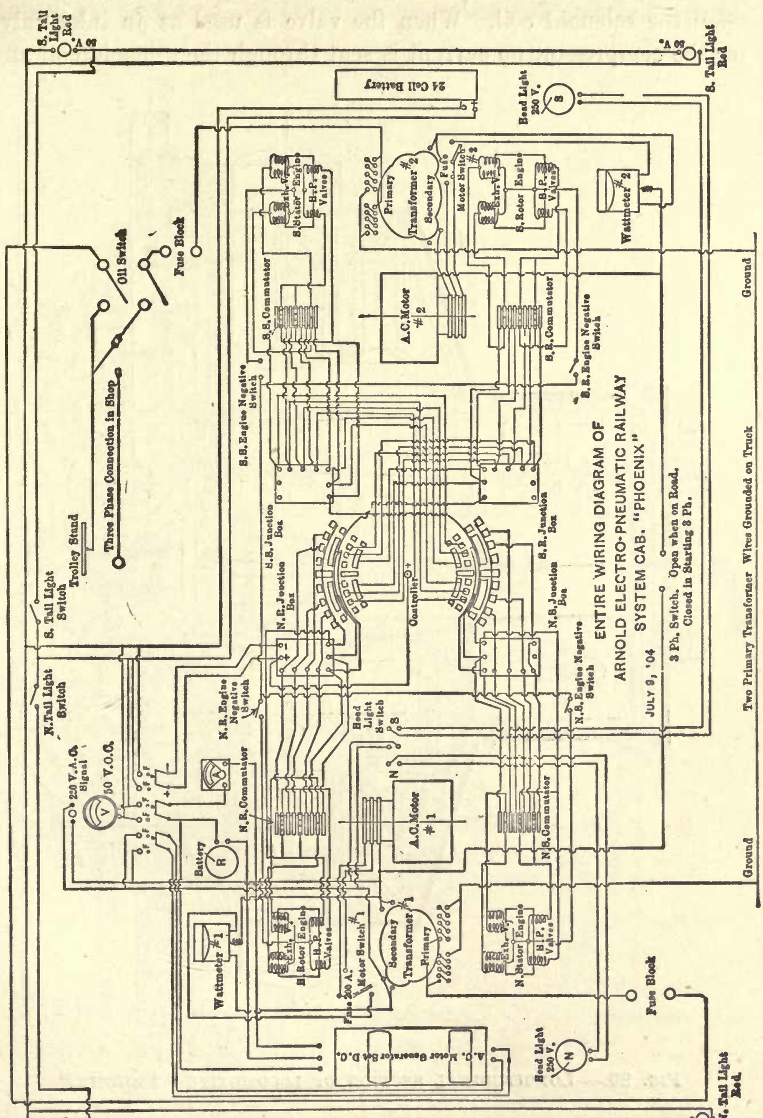


FIG. 28.— WIRING DIAGRAM OF LOCOMOTIVE "PHŒNIX."

15–83, the air thus admitted above the piston causes it to press downward, thus carrying with it and opening valve 15–83, which

will remain open and allow the air to exhaust from the cylinder into the exhaust or low-pressure space so long as current remains upon the solenoid coil. When the valve is used as an inlet valve for the compressor, no current is sent through the solenoid coil and

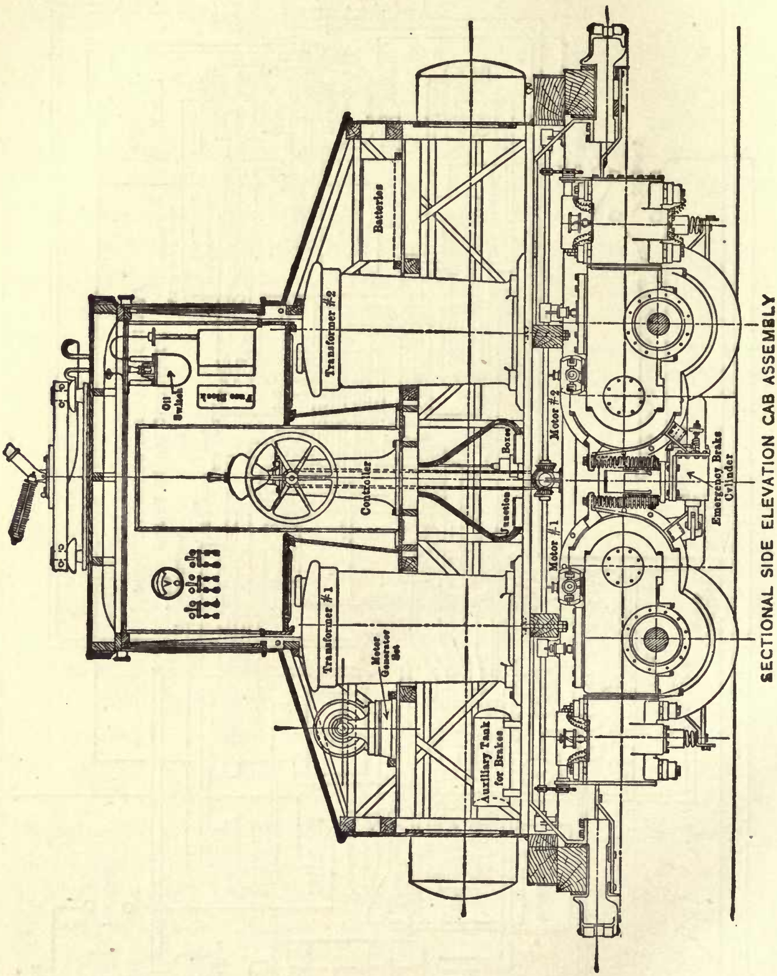


FIG. 29.—LONGITUDINAL SECTION OF LOCOMOTIVE "PHŒNIX."

the valve works mechanically, due to the suction of the piston in the cylinder, which draws valve 15–83 and piston 15–81 downward against spring 15–84, the latter being only of sufficient strength to normally hold valve 15–83 against its seat. The valves when used

for the purpose of operating the air cylinders as engines are controlled by means of revolving commutators and suitable circuits

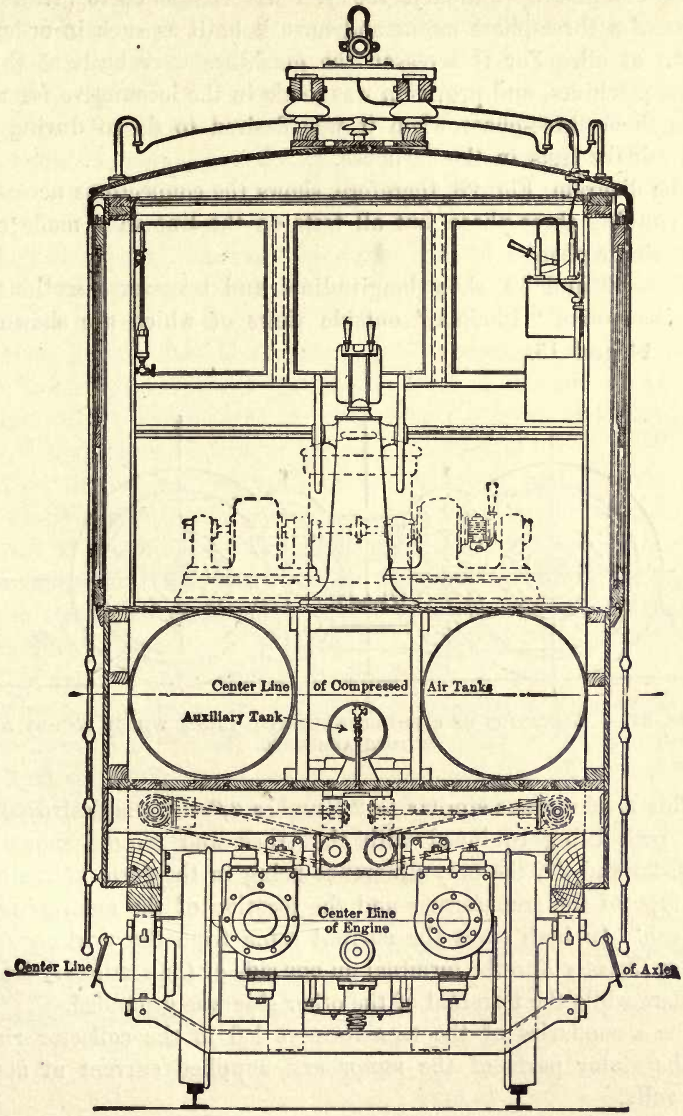


FIG. 30.— TRANSVERSE SECTION OF LOCOMOTIVE "PHŒNIX."

in combination with the controller, all as shown diag ammatically in Fig. 28.

Since it was impracticable for me to get the manufacturer to build a single-phase motor for my first machine at the time the order was placed (January, 1901), I was compelled to utilize the parts of a three-phase motor and have it built as such in order to get it at all. For this reason the machines were built as three-phase machines, and provision was made in the locomotive for running them three-phase when it was desired to do so during the preliminary tests in the carhouse.

The diagram, Fig. 28, therefore, shows the connections necessary for running three-phase, but all tests on the line were made running single-phase.

Figs. 29 and 30 show longitudinal and transverse sections of the locomotive "Phœnix," outside views of which are shown in Figs. 14 and 15.

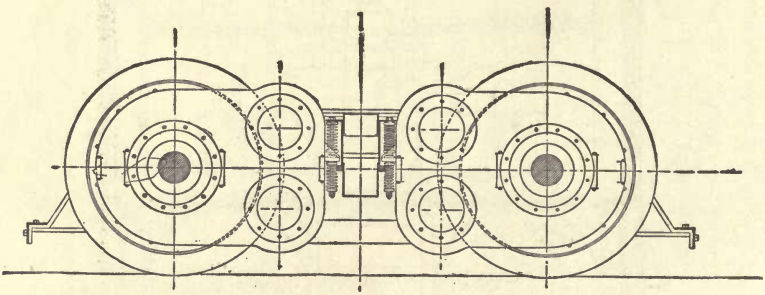


FIG. 31.— ELEVATION OF ELECTRO-PNEUMATIC TRUCK WHERE ROTARY AIR MOTORS ARE USED.

This machine was similar to "Number 2," the one destroyed by fire, both being equipped with the truck and motors shown in Figs. 22 and 23, the only difference being in the form of the cab, the type of the transformer and the location of the auxiliaries in the cab. In both cases the current came from the working conductor directly into the terminal on one side of the stationary transformers while the terminal of the other side was grounded.

The secondaries of the transformers led to the collector rings of the stator parts of the motor and supplied current at about 250 volts.

In order to permit the machines to operate as independent units by using air, each was supplied with a motor generator and a storage battery to supply energy for operating the valves of the engines.

While the development of this system has proven to be a most interesting and fascinating field of work, I regard the machine in its present form as somewhat complicated for commercial application, for like most all new mechanical problems the first designs are much more complicated than subsequent experience finds necessary.

By the development of suitable rotating air machinery the system is capable of great simplification, as by this means all of the above mentioned reciprocating parts, valves with their revolving collector rings and connections, together with the motor generator and battery disappear. The machine would then take the form shown in Fig. 31 and be controlled entirely by two valves similar to those shown at the top of Fig. 25.

If the motors then be designed for the working pressure of the line, the transformer will also disappear from the car; and as the current is not manipulated in controlling the speed of the car, the use of high-pressure motors becomes practicable.

What the commercial value of the system is will depend upon the results shown by future tests, and on the relative merits of the various single-phase systems that have been developed since the announcement of the principles of this system were made public at the Great Barrington Convention of the American Institute of Electrical Engineers in June, 1902.

Whatever its value may be commercially, I believe its influence in stimulating others to greater effort along new lines cannot be denied, and that the art of electric railroading is one step nearer its final solution than it would be today had my efforts not been exerted in this attractive field of achievement in which I have publicly,[3] and often unsupported, proclaimed my faith in the ultimate supremacy of the alternating-current motor for railway work.

3. See *Transactions* American Institute of Electrical Engineers as follows: Joint meeting with the British Institution of Electrical Engineers, Paris, August 16, 1900; Niagara Falls Convention, August 24, 1901; Great Barrington Convention, June 19, 1902; New York Meeting, Sept. 26, 1902

ELECTRIC TRACTION ON BRITISH RAILWAYS.

BY PHILIP DAWSON.

INTRODUCTORY.

The introduction of electric traction on British railways is a subject of great interest, but can only be discussed very briefly in this paper.

The position of our railways is one which is beginning to make all those connected with these interests fully alive to the necessity of improvement, both as regards increasing their freight and passenger traffic and reducing the working expenses. Owing to the stringent regulations imposed by the Government, and the very densely-populated districts which the railways traverse, the capitalization of English lines is exceedingly heavy, as the following figures clearly show:

CAPITALIZATION AND MILEAGE OF RAILWAYS IN THE UNITED KINGDOM IN 1901.

Debenture stock	£304,577,862
Preferential share capital	310,819,740
Guaranteed share capital	114,293,436
Ordinary share capital	454,379,107
Total capitalization	£1,184,070,145

Double or more lines, length of route	12,272 miles.
Single line	9,806 "
Total length of route	22,078 miles.

The ever-increasing taxation, as well as of the competition which the railway companies are beginning to feel in consequence of the rapid introduction of electric traction on tramways in and around

all the large cities of Great Britain, are some of the many reasons which, notwithstanding the fact that the total number of passengers carried, as well as the total merchandise and goods conveyed, has been more or less steadily rising, has contributed, as will be seen by the following table, to reducing the percentage of net receipts to total paid-up capital:

SUMMARY OF RAILWAY RESULTS OF THE UNITED KINGDOM FROM 1850 TO 1901.

Year.	Total number of passengers carried (exclusive of season ticket-holders.)	Weight of goods and minerals conveyed, Tons.	Percentage of net receipts to total paid-up capital.	Percentage of working expenditure to gross receipts.
1850.....	72,854,422	....	....	....
1860.....	163,435,678	89,857,719	4.19	47
1870.....	336,545,397	....	4.41	48
1880.....	603,885,025	235,305,629	4.38	51
1885.....	697,213,031	257,288,454	4.02	53
1890.....	817,744,046	303,119,427	4.10	54
1895.....	929,770,909	334,230,991	3.80	56
1899.....	1,106,691,991	413,623,025	3.61	59
1900.....	1,142,276,696	424,929,513	3.41	62
1901.....	1,172,395,900	415,593,441	3.27	63

The question, therefore, arises as to what our railways can do in order to increase the ratio of net receipts to the total paid-up capital. In my mind the answer is, that their salvation lies in the judicious adoption of electric traction.

Railways have to deal with three classes of traffic. 1). The short-distance, suburban, and interburban traffic in the neighborhood of our large towns and between the large centers which, in many parts of England, lie so close together; as for instance, such cities as Bradford, Leeds, Halifax, Blackburn, and the numerous towns on the borders of Lancashire and Yorkshire. 2). The long-distance, main-line traffic. 3.) The goods traffic.

As regards the suburban and short-distance interurban traffic, there is no doubt that electric traction will be a great benefit to the railways, and owing to the dense population of this country which makes the building of new roads expensive and difficult, and the very extensive network of railways which already exist, the steam railways in Great Britain are in exceptionally favorable conditions to benefit by electrification.

As regards long-distance, main-line traffic, there may be individual isolated cases where, after electric traction has been introduced on suburban lines it may be found advisable to extend it to the main lines.

English railway companies have progressed very considerably of late; the track construction is as good as any to be found in the world, and the locomotives, signaling apparatus, and rolling stock are, as far as steam traction is concerned, beyond criticism. At the same time, as already pointed out, the competition of electric tramways, and the demands of the public for increased facilities of locomotion, call for a development on entirely new lines. As trustee to many millions of the public for money, it is evident that no railway company can take any action or adopt any novel system involving considerable expenditure, except with the greatest care and after most thorough investigation. Necessarily, the railway companies would prefer to be perfectly certain of the results before taking any important steps, and to know what has been achieved financially by electrification of other lines. The figures of the cost of operating, and receipts on the tube lines and on the Liverpool Overhead, are very instructive, but at the same time, owing to the different conditions under which they are constructed and operated, their results do not necessarily apply to all cases. It will be some years yet before reliable information is available of the results obtained on the Lancashire and Yorkshire, and North Eastern, and under these circumstances the experience of the Mersey railway is most useful.

The conversion of the Mersey line was taken in hand and was in progress during 1902 and was completed in May of last year, and, therefore, it could hardly be said to be in full working order during the latter half of last year, for which accounts were available. Under these circumstances it is not necessary to go into these accounts in detail, but it will be interesting to note that the three minutes' service adopted has caused their train mileage to be increased from some 155,000 miles to over 401,000 miles in six months. That this result was justified is shown by the fact that the number of passengers has increased from 2,844,708 to 4,153,777, and the results show that the traffic was almost entirely made up of first and third-class passengers, the second class having to be greatly diminished, as might have been anticipated.

The results consequent on the electrification of the Milan-Varese line of the Mediterranean Railway Company are no less surprising. For six months ended June, 1903, the total number of passengers carried was 2,977,812. During the whole year 1900, when the line was entirely operated by steam, the total number of passengers carried was 2,768,541.

SUBURBAN AND SHORT-DISTANCE INTERURBAN TRAFFIC CONDITIONS.

The position of railways with respect to suburban traffic varies considerably with their location. In some cases there has been a decrease both in the number of passengers carried and in the gross receipts, due in a large measure to the competition of paralleling electric tramways. In other cases there has been little or no change, whilst in others again, particularly those serving the London suburbs, the requirements of the traveling public are so great that the steam railways have never been able to cope with them, and consequently the presence of competing tramways has not as yet been seriously felt.

The electrification of the tramways in all the big towns, as well as the construction of a large number of so-called light railways connecting the various towns, and the activity shown, both by the local authorities and private companies in promoting new lines, is rapidly bringing matters to a crisis. The speeds allowed on tramways are consequently being increased and there seems but little doubt that on a large portion of the electric lines the average speeds of from 12 to 15 miles an hour may be allowed at no very distant date. This increase in speed, as well as the frequent service given by electric tramways, will make them most serious competitors to steam railways unless their local time-tables are considerably modified and improved, both as regards frequency and average speed, and this will only be rendered possible by the introduction of electric traction.

Thus there is an urgent need for a revision of the mode of transport adopted on railways, in one case to turn the ebbing tide to traffic, and in the other to satisfy the claims of a public anxious to travel but unable to do so because of the congested state of the lines. If the railways allow competing lines to proceed unmolested, the problem will be solved in a manner extremely detrimental to the former. The congestion will steadily diminish by reason of the traffic being diverted from the railways by the opposing interests, which will give the facilities so urgently needed at the present day.

The suburban traffic of the railways has been growing rapidly with the suburbs, and as it is largely concentrated at certain stations instead of being uniformly distributed, it is naturally very congested. The state of affairs is further complicated by the inter-

mingling of main line and suburban traffic in the termini, owing to lack of space which prevents their being kept entirely separated as they should be; and by the delay due to the impossibility at present of getting in and out of the terminal stations expeditiously.

The electric tramways, though strong and healthy, are at present a young growth, but they are extending with amazing rapidity in all directions, with the result that they are pressing hard upon the railways, even in the matter of comparatively long-distance suburban traffic; this is a branch which is essentially a province of the railways, and one in which they should easily maintain their supremacy if they are properly equipped to satisfy the requirements of the situation.

The great need of the railway companies in respect of their local traffic is both to increase their service and to improve their methods generally, and there is only one practical way of doing this, viz., electrification. Under the present conditions it is impracticable to increase the frequency of suburban trains, first, because of the cost of handling such an increase by steam locomotives, and secondly, because of the mutual interference of the main line and suburban traffic. In other words, the lines are at present being worked very near to the limit of their capacity as far as steam is concerned.

In the case of suburban trains the amount of time occupied in starting and stopping forms a very large proportion of the whole time spent on the journey, so that a very considerable saving would be effected if this waste of time could be reduced. At the same time it is essential that this should be supplemented by more efficient methods of taking up and detraining passengers, which process, under the present circumstances, entails an unnecessary waste of time at stations.

Attempts have been made in various cases to avoid the electrification of steam lines by the adoption of special locomotives giving exceptionally high rates of acceleration, but the failure of these has only served to emphasize the necessity for electric traction, for by that means alone is it possible to obtain really high rates of acceleration. Experience has conclusively shown that the only really satisfactory method of handling suburban traffic is by means of electric traction, and it is a great pity that hitherto the question has not been faced with greater boldness by those concerned.

There are such certain benefits to be derived from the electrification of steam suburban lines that the only wonder is that more

progress has not been made. As already stated, the main advantage is that the use of electric power by permitting very high rates of acceleration enables the frequency and consequently the carrying capacity of the service to be largely increased, while at the same time the working expenses per train mile are decreased. Also with electric traction the delays due to signals are of less importance, owing to the quickness with which an electric train can get under way. Over and above the foregoing, the cleanliness of electricity and the consequent enhanced comfort of the passengers is a considerable factor in increasing the popularity of the line.

Not a few railway companies have expressed their opinion that they have no objection to the tramways taking their suburban traffic. According to them this branch of the service is both costly to maintain and difficult to manage, and at the same time it is not a profitable source of revenue, and they appear to be quite content to drop it altogether and fall back upon the lucrative main-line traffic. There are, however, two objections to this. In the first place, it is extremely doubtful whether any railway would be allowed by the Government to drop its suburban traffic completely. In the second place, there is too much capital tied up in this branch to render it possible to dispense with it entirely. Few companies could afford to let such a large amount of capital lie idle, and there is no reason why they should. In my opinion, there is not a single railway company that could not operate its suburban traffic in the neighborhood of most of our large manufacturing towns at a substantial profit if it were to be electrified, and in most cases the profit resulting therefrom would be more than sufficient to pay the interest on the necessary capital outlay called for by the change of motive power.

As soon as the railways electrify their suburban lines, they will hold a very strong position against the attacks of competing tramways and light railways, since in the matter of speed they will have all the good points of the tramways, without the disadvantage of having to operate in crowded thoroughfares; the greater distance between the stops will naturally permit a far higher schedule speed to be maintained, and the higher the speed the railways are able to offer to the public, the shorter will be the distance of the journeys for which the tramways will prove more convenient.

That there is room for great improvement in the railway service, and that there is a larger amount of latent traffic to be secured pro-

vided the railway companies go to work in the proper way, is clearly shown from the statistics giving the number of times the population of the large cities in Great Britain are carried annually.

The evidence given before the Royal Commission for London Traffic by Mr. Edgar Harper, the statistician of the London County Council, shows that whereas, in 1867, the population of London was carried 22.7 times, in 1901 it was carried 128.7 times. These figures only deal with the traffic in the London area, and do not include the passengers brought in by suburban trains.

It must be noted that these figures do not include all the omnibus lines.

It is interesting to note that the number of journeys per head of population in London is at present small compared to that in many other large cities, as will be seen by the following figures:

London, 1901	129	journeys.
Glasgow, 1901	174	"
Liverpool, 1901	187	"
London (Mr. Harper's estimate), 1903	200	"
Berlin	223	"
Greater New York	320	"

Facilities for traffic always create traffic, and as facilities are improved traffic will not only be actually but also relatively greater. This is shown by the following figures.

INCREASE IN NUMBER OF JOURNEYS PER HEAD OF POPULATION.

Greater London.		Greater New York.	
1867	23	1860	47
1870	27	1870	118
1880	55	1880	182
1890	92	1890	283
1900	126	1900	320
1901	129	1903 (estimated)	415
1903 (estimated)	200		

From these figures it will be seen that the population of London is carried only half the number of times that the population of New York is.

Conditions to be Fulfilled for a System of Electric Traction to be Satisfactory.

There are certain conditions which require to be fulfilled before any system can be considered capable of giving satisfactory results, and these conditions are briefly set forth below.

1). Should moving machinery be found necessary in the transforming of sub-stations, these stations must be as few in number as possible. The apparatus used in sub-stations should be such as to require but little attendance and should be efficient at all loads and capable of dealing for short periods with very heavy overloads.

2). The number of conductors required to supply current to trains should be as few as possible, and should be capable of unlimited extension, and must not interfere with the tracks; hence the use of a third rail is not possible.

3). It must be possible to collect from a single conductor sufficient power to haul one or more fast trains in service on the lines between the feeding points of the conductor.

4). It is very desirable that the system should be applicable to main line as well as suburban traction, and that it should be possible to utilize at least two working pressures — a low pressure where found necessary in or near the station, and a higher pressure outside.

5). The system should be such that the trains can be operated at any speed required, and thus be capable of making up lost time.

6). All controlling apparatus must be of the simplest character, and such that no skilled labor is necessary to operate the trains; also there must be no dangerous high pressure anywhere accessible to either railway officials or passengers.

7). If alternating currents are used it is essential that the power factor be high and that the motor be capable of giving an acceleration equal to that obtained with the best series-wound direct-current motors at present in use.

8). In certain cases it might be advantageous for the motor to be constructed to return current to the line, but in any case it must be constructed to reverse and to be used for braking purposes.

Overhead Conductors.

The doubts that have been expressed as to the feasibility of adopting overhead wires on the lines where steam locomotives are running, and the objections which have been urged against their use

on this account, are, in my opinion, quite groundless, and there is no reason to anticipate any trouble from this cause. The engineers of the Valtelina railway informed me on the occasion of my last visit that they had never experienced the slightest difficulty in respect to the two overhead 3000-volt conductors which have been in use for over two years on that line, in spite of the fact that steam locomotives burning soft coal are continually passing over the line, and that the aerial conductors in some places have to pass through tunnels from the roof of which large quantities of water are always descending.

The conditions I have mentioned as being those with which a traction system has to comply appear to be exceedingly difficult to fulfil, and the only system which could possibly comply with the conditions is a single-phase one. As long as electric traction was applied only to tramways or lines with few or no complicated junctions, and on which only electric trains operated and there was no steam service, the continuous-current railway motor has given perfect satisfaction.

But this type of motor has its limitations, and the necessity for dispensing with third rails and using a single high-tension overhead conductor, has recently induced manufacturers and directors to investigate the question thoroughly and experiment upon the possibility of constructing a really reliable single-phase motor.

As might have been expected, as soon as there was a real demand it was not long before an article was produced to supply it. Aided by the experience obtained in the design of all types of electric machinery, consequent on the enormous extension of the applications of electricity that has taken place during the last few years, a satisfactory alternating-current single-phase motor has now been developed.

The single-phase motor at present developed may be divided into two classes, the "series" type which has been investigated and brought out in Europe by Dr. Finzi, and in America by Mr. Lamme, and the "repulsion" type, both in the original form as investigated many years ago by Prof. Elihu Thomson, and the "compensated repulsion" form as theoretically studied and discussed by Mr. Latour in France, and practically investigated by Messrs. Eichberg and Winter.

The restriction as to the pressure at which it is feasible to operate a continuous-current motor is a great drawback to its employment on electrified railways, for it means that the sub-stations must be

placed close together. The use of an alternating-current motor introduces a considerable saving in the cost of distributing mains and conductors on account of the high voltage which can be utilized, and not only are the sub-stations fewer in number, but they are smaller and cheaper in first cost, maintenance, and attendance, owing to the absence of rotating machinery.

The great advantage of the single-phase motor in dispensing with the necessity for a third rail and enabling a single small high-tension overhead conductor to be used instead is further enhanced by the fact that in its operation the rheostatic losses involved in the control of continuous-current motors are avoided. An additional gain in efficiency also results from the better distributions of the sub-stations and the decreased losses at these points of distribution, whilst in some cases a line voltage can be employed which is sufficient to dispense entirely with transformer sub-stations. Also owing to the increased efficiency of the whole system the amount of plant required at the power station is less than would be the case for a similar direct-current system.

A very important point about the single-phase motor is the fact that it can easily be adapted to operate upon direct-current circuits, a simple switching device being all that is necessary to make the change.

Besides the solutions mentioned above, there have been various more or less unpractical solutions suggested, such as that proposed by the Oerlikon company and now being tried by them.

Conditions to be Fulfilled by Conductors Bringing Current to Train.

The conditions governing the type and position of the conductor from which the motor cars or locomotives obtain their supply of power in the case of most of the steam suburban railway systems of Great Britain are very different to those which apply to ordinary tramways, newly-built electric urban or suburban systems.

On most suburban systems the traffic is very dense and either local long-distance passenger, or goods' trains are operating over the lines for the greater portion of the 24 hours for six days a week. At many junctions the traffic is largely increased by the numerous other companies who use that station and there is but little time available for keeping in proper repair the existing track rails and points and crossings, which are very congested. As things stand at

present the tracklayers have the greatest trouble in finding time to keep the permanent way in proper condition, and they are greatly hindered in their work owing to the very frequent service of trains.

Under these conditions, the introduction of a third "live" rail is practically impossible. Even if it was guarded it would constitute an additional and constant source of danger to the permanent way men who, besides having to avoid the passing trains, would also have to keep clear of the "live" third rail.

Furthermore, it is highly probable that a "fourth" or return rail, such as has been adopted on the Metropolitan district and the Lancashire and Yorkshire, would be found necessary in order to keep within the 7-volt drop in the return circuit required by the Board of Trade.

It might be possible to sectionize the third rail, and arrange so that no portion of it was alive except while a train was actually passing over it; but the necessary automatic switches would introduce most undesirable additional complications, whilst there would always be a possibility of their failing to work so that it would not do for the men to treat the rail as quite harmless.

In any case, with the complicated track work existing at many large junctions it is probable that there would be no space available to place the third and fourth rail, owing to the numerous signal wires and the rods used to operate the points.

The consequences following even a slight derailment would be most serious and the danger of fire due to short-circuits thus incurred, would be very great, not to mention the danger of electric shocks to passengers and the entire stoppage of the service for a considerable time, while the damage to the third rail was being made good.

These considerations have led a large number of railway managers and engineers in the United Kingdom, on the Continent, and in America, to the conclusion that the idea of using any "live" rail conductor installed at or near the level of the track rail must be discarded.

The only other alternative is to employ an overhead conductor. From a careful study of the conditions which have to be fulfilled, I have come to the conclusions embodied in the following:

1). The conductor must be overhead.

2). The conductor must be as far as possible at a uniform height above the track rails and have no sag.

3). The conductor must be supported in such a way that it is practically impossible for it to fall down on the track and get in the way of the train, even in the event of its breaking.

4). The current collector must be light and require little or no attention. Any wear must take place mainly on the collector and not on the overhead conductor.

5). The collector must be such that it cannot slip or slide out of contact with the conductor.

6). In the event of the collector fouling any portion of the overhead work, the collector should give way and not the overhead work.

7). The collector must be cheaply and easily replaceable.

8). The overhead conductor must be connected to safety devices that will automatically cut it out of circuit the instant any breakage occurs.

9). The insulation of the conductor and collector must permit the use of very high pressures, say, up to 10,000 volts.

I have designed a form of construction which I think will meet all requirements and which will obviate any interruption of service taking place. Furthermore, I would propose, as far as possible, not to use steel and iron except for poles or brackets and to avoid the employment of galvanized wire or hooks in any form or shape whatever. The supporting wires would be stranded wire, composed of either steel covered with an outer layer of copper rolled onto it, or else composed of phosphor or silicon bronze wire; the main conductor from which current would be collected would be of hard-drawn copper and of a diameter of at least one-half inch; the supports of this wire should not be more than four feet apart and, therefore, it would be possible to hang this wire in such a way that to all intents and purposes it would be absolutely parallel to the track rails.

Current Collector.

The question of the form of current collector or trolleys to be used is one which will have to be most carefully considered. The Oerlikon company's type of trolley loses most of its special advantages when the conductor is suspended from above, over the tracks. With the wire in this position it acts almost exactly like an ordinary sliding bow, and is in no way superior to that type of collector. The chief merit of the Oerlikon trolley lies in its wide range of movement, and in the fact that it can be arranged to make

contact with the conductor either on top, underneath, or at the side. But necessarily the first and last positions require a special form of construction of the overhead work, and are quite impossible where the conductor is suspended from span wires, whether longitudinal or transverse.

For main line work where there are no complicated crossings or sidings, it is quite possible that the form suggested by the Oerlikon company may be adopted with the greatest advantage.

Bow trolleys may be divided into two classes, one of which is the ordinary scraping type, as used by Messrs. Siemens & Halske, and which is the more common. With the operation and construction of this trolley I am fully acquainted. Such bows have been running for many years, the soft metal on the top of the bow which make the contact preventing wear of the trolley wire. The contact piece is easily replaceable when it wears out.

The other type of trolley is that designed and constructed by Messrs. Ganz & Company and used by them on the Valtelina line; this trolley instead of a scraping bow has a roller mounted on ball bearings. This type is considerably more expensive than the scraping trolley and I do not see any necessity for the additional complications introduced by the use of a revolving roller.

In connection with trolleys the question may arise as to whether any difficulty is likely to be encountered from the high speed at which the trolleys will run along over wire, but there is no reason to anticipate any trouble on that account. In the experiments carried out on the high-speed experimental electric railway between Berlin and Zossen, the bow was only pressed against the wire by a pressure not exceeding from 3 to 4 kgs, whereas the ordinary trolley has to be pressed against the wire with a pressure between four and five times as great; this smaller pressure is of course advantageous as it reduces the wear and tear on the trolley wire and makes it possible to have a much lighter trolley construction than would otherwise be the case.

In my opinion a trolley of the "scissors" type would present many advantages. The contact bar could be made at least as long as the whole width of the carriage and this would allow considerable latitude in the position of the overhead wire. In situations where there was not sufficient room for the conductor to be suspended over the center of tracks, it could be diverted to one side, and increased head room thus be obtained by reason of the curvature of the top of the carriage. In this way it would be quite possible

to place the conductor at an altitude not greater than the highest point of the carriage roof, and thus obtain the necessary clearance. In places where it might be considered inadvisable to place a bare conductor under very low bridges, this portion might be made "dead," electrical continuity being obtained by insulated cables. With this arrangement a dummy trolley wire would be provided for the trolley to run on whilst passing under the bridge.

There is no reason to fear that a "scraping" contact would not be satisfactory, since there is ample evidence to the contrary. Many years' experience with third-rail working has demonstrated that very heavy currents can be collected in this way, and with the single-phase high-tension system the current per trolley would be very small; in fact, it would probably be considerably less than the amount which is frequently collected by small trolley wheels in ordinary practice.

Advantages of Electric Traction.

There are several further advantages possessed by the modern method of traction which render it greatly superior to steam haulage, quite apart from the fact that the high acceleration demanded for the proper operation of suburban traffic can only be obtained from the use of electric power.

In the first place steam trains have to carry their own power; that is to say, a locomotive must not only be able to haul a certain weight of train, but it must carry coal, and machinery to consume that coal and convert its heat energy into tractive energy "en route," and a steam locomotive is a most uneconomical instrument for transforming heat into work for traction purposes. All this adds to the weight of the train and greatly increases the weight to be hauled per passenger. In the case of some of the trains on the suburban systems serving London, the locomotives weigh over one-third of the total useful weight of passenger coaches hauled.

In the modern electric system the heavy locomotive is replaced by a comparatively light motor car, and energy is generated under the most economical conditions at a certain power station from which it can be transmitted many miles with but slight loss.

The wear and tear of the permanent way, particularly at junctions and crossings, would be considerably less with electric traction than with steam traction, as in the former there is not that tendency to roll or pitch which exists in the case of steam loco-

motives and which is due to the movement of their reciprocating parts.

Electric trains with two or more motor cars on the multiple-unit system have the great advantage of distributing the weight of the train more evenly over the track and also of permitting a smaller weight on each driving axle than would be the case with a locomotive, owing to the larger number of driving axles. A steam locomotive has to be heavy enough to give sufficient weight on the driving wheels to haul the heaviest train up the steepest gradient, at the highest required speed. This concentration of the weight is very detrimental to the track, and the bad effects are accentuated by the pounding action caused by the reciprocating motion of the engine.

For the same weight on the driving wheels an electric motor can exert a much greater tractive effort than a steam engine, because the electric motor exerts a constant torque upon the driving wheels, whilst the steam engine does not. In the case of steam locomotives, the ratio of the maximum tractive effort to the weight on the driving wheels is not much above 16 per cent, whereas experience has shown that with electric traction this is increased to from 25 per cent to 30 per cent.

The cost of operating electric trains will also be reduced by the fact that only one man is required, that is to say, only a driver instead of both a driver and a fireman. The Board of Trade should take no exception to this, as should the driver be incapacitated in any way, the method of control employed is such that it automatically brings the train to a standstill. The men for operating these trains need not be mechanics, and the work will be cleaner and nicer, and, therefore, sought after, as in the case of electric trains, the driving cabin is entirely inclosed and perfectly clean.

Electric traction is much more flexible than steam, and trains can either be split up into units of one or two cars or joined up into trains, the length of which is only limited by the length of platform available.

There are other advantages, but the crowning one is certainly the much higher average speed due to rapid acceleration and the economy of power and labor, as well as the reduced cost of production which is everywhere effected.

An incidental advantage in favor of the electric motor as compared to the steam engine is that the former can stand an amount

of continuous service and hard usage which would be impossible with the latter, besides having far less internal friction.

A most important benefit resulting from the use of electric traction is the diminution of the present difficulties due to the lack of accommodation in termini. Mr. Aspinall, the general manager of the Lancashire & Yorkshire railway, stated to me that the recent electrification of the line from Liverpool to Southport will not only double the carrying capacity of the line but will also practically double the terminal accommodation.

How this is brought about is easily seen when we consider the time wasted at present in getting a steam train out of a station after it has once entered. First the line has to be cleared to allow another locomotive to back on to the train in readiness to take it out, which it does. Then before another train can be brought in the line has to be cleared again so that the original locomotive which brought in the first train can run out. These various manœuvers occupy a considerable amount of time, besides necessitating a considerable amount of siding accommodation, not to mention possible blocking of other lines by the steam locomotives constantly either running out or else backing on to the trains.

Conclusions.

Comparatively little has so far been done toward the introduction of electric traction on main line railways in Great Britain. This is not surprising, and as far as that is concerned, neither in the States nor on the Continent of Europe are main line railways at present operating anything like very long stretches of line by means of electric traction. The country which has the longest stretches of line is undoubtedly Italy, with its three-phase 3000-volt line working with overhead trolley between Lecco and Sondrio, and its third-rail system between Milan, Gallarate, and Varese, both of which lines have been exhaustively described in the technical press of the world. As regards this country, the Lancashire & Yorkshire railway has equipped and is operating 23 miles of route, and the North Eastern is operating 40 miles of route, both on the third-rail system. These lines have only recently been put into regular service, and no figures, either as regards increase of traffic or cost of operation, are as yet available; the only results so far obtained go to show the excessive danger of third rail. In this country a large number of accidents to third parties have taken place, some of

them fatal, and in one instance a train has been set on fire and seriously damaged, fortunately with no loss of life. These results, as far as they go, amply confirm the conclusions at which I have arrived and are strong evidence that the adoption of third rails, at any rate on main line railways, is not at all desirable.

There are several lines in this country operating at high speeds with fairly heavy loads and many others are being constructed. There is, for instance, the Mersey railway, the City & South London, the Central London, the Great Northern & City, and the Liverpool Overhead, all of which have been working most satisfactorily for a considerable number of years, as well as the Metropolitan, the Metropolitan District, and other tube lines now being constructed by the Underground Electric Railway Company of London and which will commence working next year. The power station which will supply energy for the last-mentioned railways is, so far, the largest that has ever been built.

To give some idea of the large amount of railways which already exist in London, the following tabulated statement may not be without interest. I have taken them from figures published by that eminent American, the Hon. Robert P. Porter:

RAILWAYS RUNNING INTO LONDON.

North Side.

Railway.	Length of lines within county. (miles).	Number of stations within county.
Great Central	2.37	1
Great Eastern	16.79	27
Great Northern	4.31	4
Great Western	4.75	4
London & North Western	9.64	12
London, Tilbury & Southend	.62	1
Metropolitan	12.25	18
Metropolitan District	10.42	16
Metropolitan & Metropolitan District (joint)	2.12	8
Midland	7.27	6
Totten & Hampstead Junction	1.92	6
Total	72.46	103

South Side.

Railway	Length of lines within county (miles).	Number of stations within county.
London, Brighton & South Coast	31.14	29
London, Chatham & Dover	26.22	33
London & South Western	14.05	12
South Eastern	37.86	27
London & South Western and London & South Coast (joined)	.60	—
Totals	109.87	101

Wholly in London.

City of London Electric	6.50	13
City & South London Electric	6.65	14
East London	7.22	7
Hammersmith & City	3.00	5
North London	11.19	18
Waterloo & City Electric	1.50	2
West London	2.30	2
West London Extensions	4.76	4
Whitechapel & Bow	3.00	4
Totals	46.12	69
Making a grand total of	228.45	273

In this connection it must be borne in mind that the mileage here given are miles of route and not miles of single track, and that they only represent the miles of route actually inside the county of London. In order to represent the actual mileage which is only, or to a large extent, devoted to suburban service, the total would have to be more than doubled; in the case of the London, Brighton & South Coast railway only just over 31 miles of route are given, whereas the suburban system comprises 75 miles, and on this system, the average distance between stations does not exceed one mile. A glance at a railway map of London and its environs clearly shows the enormous network of railways which converge into the center of the city, and a careful examination of such a map on which the existing electric tramways and light railways have been drawn will

show how, in the next few years, the electric tramways and light railways will enable passengers to travel from any portion of London to places from 20 to 30 miles outside the center of the city. Under the existing conditions it would in many cases be advantageous for passengers to travel as far as 15 miles by tramway instead of taking the steam railway, owing both to the low average speed and, in many cases, the long interval between the trains.

What has been stated as regards London, applies quite as well to other large towns of the United Kingdom, and I am firmly convinced that there is no country in which electrification will be a greater benefit to the railways than the United Kingdom. I believe that the British railway companies are rapidly realizing that a move will become necessary, and when once the movement begins, the transformation as regards our railways will be quite as great as that which has taken place during the last few years with tramway construction.

Discussion.

Chairman Duncan: The paper abstracted by Mr. Armstrong is now open for discussion.

Mr. H. Ward Leonard: There is one figure that drew my attention in the early part of the paper, and that is the statement of the very high capitalization of the English roads, as an average. I can only speak from memory, but I believe that the most efficient railway as regards earnings we have — the Pennsylvania railroad — has a capitalization of about $370,000 per mile,— which is about 50 per cent in excess of the figure named. So that very high capitalization, while of course it is of tremendous importance, is not necessarily an indication of poor earning capacity. The average figure in New York, Pennsylvania, and New Jersey which is the part of the United States most fairly comparable with England is about $120,000 a mile.

Mr. F. J. Sprague: You refer now to single or double tracks? And does the paper refer to single or double tracks?

Secretary Armstrong: It is per mile of road. It is partly single and partly double.

Mr. Leonard: The figures I have named are all per mile of road. The figures I have stated are from the statistics of the United States Railway Commission Reports. They are per mile of road, that is, per mile of line.

I think it is quite proper to emphasize the statement the author has made in the paper as to the steam locomotive having to carry around with it continuously a very large number of tons that are entirely idle. I think it would probably be conservative to say that the net cost represented by the ton miles of a locomotive due to the non-tractive part of a heavy freight locomotive in this country would be not far from $50 per day. And that brings up another point, namely, that in discussions on this subject, a great deal of attention is usually spent on the cost of

fuel, and the question of whether or not it would be possible to save the wages of the fireman. Personally, I consider all those matters as extremely trivial as compared with the really important matters. Considering $100 of earnings by railways of this country only about $7 of that amount is spent for fuel. So that it does not seem advisable to confine the discussion so much to fuel consumption.

I think that the very greatest importance should be laid upon the requirement of endeavoring to utilize to the highest degree the very large investments and fixed charges that are represented by the equipment and maintenance of a mile of road. Something like 86 per cent of the total cost of moving a ton-mile is represented in this way, and is totally independent of the coal and wages on the train. And it seems to me conspicuous that the problem narrows itself down to the question of getting from every mile of track per hour the maximum possible ton miles — which means again the maximum possible number of tons moved at the highest possible rate of speed.

If we go back, for example, in the statistics of the Pennsylvania Railway for about thirty years we find that the cost of moving a ton one mile used to be at that time about a cent and six-tenths; and in 1902 the cost of moving a ton one mile by the same railway was thirty-six hundredths of one cent. Now, this very striking reduction in the cost of moving freight has not been in any way due to any reduction in cost of wages or cost of coal. On the contrary, those have increased. And personally I am strongly of the belief that to-day the cost of moving freight is inversely proportionate to the power that is employed in moving the train, and with that thought in mind it seems to me that the electric moving of freight has possibilities that are not at all to be expected from any steam operation.

There are probably not more than 10 per cent of the locomotives that are used in this country that are capable of developing over 1000 horsepower. Those large locomotives are the most economical ones we have as regards moving freight. There are some 40,000 locomotives in the United States, and less than 4000 of them are of modern efficient size. The boiler is the principal limitation to the power of the locomotive, and it seems unlikely that there will be very much growth in the power of the boiler used on steam locomotives; whereas, theoretically speaking, there is no limit to the amount of power that could be applied to the movement of a freight train by electricity.

The draw-bar pull of the freight locomotive, in the best types, reaches sometimes as high as 50,000 pounds, but that draw-bar pull is only obtained when steam is taken at full stroke,— which means at an extremely slow rate of speed, and by the time such a rate of speed is reached as would represent the average speed desired the draw-bar pull is less than half of that figure.

The mountain sections of our principal railways are the places where the requirements for power are most keenly felt to-day. There is always a great congestion of freight at such places. If we employ electric locomotives we have, fortunately, coincident with the grades of those moun-

tain sections, as a usual thing, power in cheap form represented by the water power of the mountain section.

It seems to me that what is wanted is a locomotive which will produce about 50,000 pounds draw-bar pull and maintain that at about thirty miles per hour — and that means 4000 horse-power at the draw-bar. We already are subjecting our draw-bars to that strain, and they are strong enough to stand it, provided that we have some form of operation which is not going to subject those draw-bars to intermittent large strains due to irregular methods of control, or to the bucking of the various units that are employed under multiple control.

It seems to me that the principal cause of the poor showing of the British railroads in the cost of handling freight, as compared with the United States, can be found in the fact that as an average the horse-power of their locomotive is very small compared with the best practice in this country.

Mr. Sprague: I have only a few words, Mr. Chairman, on this paper. Not having read it, I am not prepared to discuss it at length. Probably in what little I say I may disagree with Mr. Dawson, and to some extent with what Mr. Leonard has said. In one form or another I have for many years advocated electric traction. It has already naturally supplanted a method of traction which at the best was poor — that is, animal traction; and in supplanting it, it has achieved results in transportation greater than its most ardent advocates had hoped, in cheapening operating cost, increasing schedule speeds and opening up new fields.

But we must not forget that one of the chief reasons for the great success of the electric railway has been the fact that it has been what may be called a house-to-house railway, one making frequent stops convenient to the passenger. As a result we have seen here in the United States practically every horse-car disappear, almost all cables abandoned, existing lines consolidated, and new lines link together towns and cities and wipe out the divisions between urban and rural communities.

But when approaching the steam railway problem I have always done so with a good deal of deference to existing conditions. Electricity, after all, is merely a convenient method of transmitting power. We do not create anything by it, we do not establish any new laws by its use. By concentrating at central stations the power used on a railroad and distributing it in the best possible manner we hope to utilize that power more economically. But in order to do so successfully from a power standpoint there is one essential; the load factor must be high, which brings me back to an assertion which I have made again and again for the last fifteen years; namely, that leaving out for the moment the influence of competing lines, diversion of traffic and what not, there is a point on any railroad where the adoption of electricity may be justified, and that point is primarily determined by one essential, density of traffic. And I do not mean by density of traffic concentration of loads at one point, but multiplicity of units well distributed. So long as the operation of any road means the sending out of high powered units at long and irregular intervals over great distances we might as well be frank with ourselves and say that there is not the field for electric transportation.

As the traffic increases we approach a point where the number of units between terminal points warrants the consideration of a change of motive power, and I think that condition has arisen on a number of steam railroads. Beyond that point there can, I think, be very little question as to whether electricity can be economically adopted.

The problems in Great Britain, the Continent and the United States are somewhat different. Here it will be many years before we can in even the most hopeful attitude look for many of our main roads to be operated other than by steam. There are some roads and certain sections of railroads which will undoubtedly be operated by electricity — but oftentimes for reasons not determined by economy of operation.

I may, perhaps, cite the most important two instances in this country, if not in the world, at present — the operation of the Pennsylvania Railroad tunnels and terminals in Jersey City, New York and Long Island, and then those of the New York Central Railroad in New York and a part of its main line. I have the honor to be a member of the Commission on the latter road, which has to do with the electrification of the equipment. It is, perhaps, too soon to go into details in connection with it, except this: One of the requirements — a legal one — which determined the use of electricity on this road was that no steam-operated train should be used below the Harlem River. The Harlem River is well within the city limits of New York, and only a comparatively short distance from the terminal at 42nd Street. The movement of trains within that district is enormously congested. According to a report made by Mr. Arnold sometime ago, at certain periods there are over 700 daily train movements, and the trains vary anywhere from 150 to 700 tons in weight.

The law said we should abandon the use of steam. Of course, we were permitted to use anything else in the tunnel, but that was practically the same as saying that electricity should be used. But within even the district determined for electrical operation extending out some 35 miles, I do not think any calculation made, taking into account the interest on investment, shows any real economy in operation over steam, all things considered.

The determining considerations may be stated as first, the law which practically required the use, part of the way, which part was to a point where there were no terminal facilities whatever, and second, that it was advisable from a transportation standpoint to operate suburban trains electrically — certainly within a distance of perhaps an hour's run to New York. Having determined that, then it was common sense to operate all trains located within that zone by electricity, instead of having a duplicate system.

The result is that for some distance from New York city we will have what may be considered a great terminal, within which there are suburban trains operated by motors under the cars on the multiple-unit plan, and other trains dropping off their steam locomotives at the termini, and taking on electric locomotives likewise so operated.

It is, perhaps, unwise to attempt any limitation as to this particular development. Certainly I would not be rash enough to hazard it, but it is a special problem, and I do not think has yet any great bearing upon the

broad question whether trunk railways will be operated by electricity. There are many other problems to be taken up when that subject is considered.

The British railways, especially those terminating in London, will mostly adopt electricity only when they are compelled to; few of them will do it of their own volition. The competition which exists in this country with electric railways will not be quite so forcibly felt on English roads, because there is not that same freedom in granting of franchises for parallel lines of railways that we have here. But there is a special reason why electric equipment should be considered. The traffic in London, for example, is enormously congested at certain times of the day. The result is that the facilities are entirely inadequate, and new construction, whether of an overhead line over existing tracks, or tunnels beneath or tracks parallel to them, is almost prohibitive in cost. So that the natural, and so far as I can see about the only way, in which they can increase their capacity is by electric equipment, and I think that the British roads in time will see that fact.

Perhaps one of the most important means by which the changes could be brought about would be in the reduction of the age limit in their directorates. You gentlemen know the English and American practice is somewhat different in this regard. When a man becomes a director on an English railway the position practically terminates only at his death or permanent disability, or when for some good practical reason he gives away to another. He rarely represents, in that conservative method which governs English railways, the progressive element of the stockholders. Being a man of mature years, and often having reached that age when most men are ultra conservative, he will hesitate to abandon an existing system and adopt another. It usually takes younger men to do that, and to believe what can be accomplished by such a change.

Here in the United States the directors have not that hold upon the administration that they have abroad. A change of ownership in the road, a change in the holdings of the stock, may result in a very prompt and radical change in its management from the president down, but such a thing is almost impossible in the British Isles.

I do not know that there is anything further, Mr. Chairman, that I want to add. In fact, I did not intend to say anything. I am as hopeful, perhaps, as any one can be that electricity will be used on steam railroads, but I do not want to shut my eyes to the fact that there are a good many difficulties inherent to trunk-line railway service for which electricity is no cure-all.

Mr. Leonard: Mr. Chairman, if I may be allowed to add a word, I should like to speak of one point I have heard frequently raised and it seems a fitting opportunity to mention it. In comparing the cost of operation of English railways with American railways, I find that the Englishmen are very apt to retreat behind the argument that in England the mail and express business is classified in the freight figures, whereas we in this country have those classified in the passenger business, and receive compensation for those, which make so important a factor as to distort the figures materially; and that, therefore, deductions cannot be

fairly drawn by comparison in the cost per ton-mile of the English railways and the American railways.

The express is 2 per cent of the receipts in this country, and the mail also about 2 per cent of the total receipts, so that those figures are not sufficiently influential to in any way influence the very striking difference in the costs. About nine-tenths of our present steam locomotives in our country seem to me a liability, rather than an asset, to the railways that operate them; and since there seems to me to be a necessity for "scrapping" about nine-tenths of the inefficient small locomotives and the replacement of them by the larger efficient ones, we are not confronted with the same condition of affairs as we would be if the steam railways had already made a comprehensive equipment of the highest class of steam locomotives.

THE MONORAIL RAILWAY.

BY F. B. BEHR.

For many years eminent engineers, including the great Telford in 1828, have taken great interest in designing single-rail railways, and many patents, covering a variety of forms and combinations, have been taken out, but none of these attempts have been carried to a practical issue until recently. Within a comparatively recent period, however, two systems have been so far perfected as to offer real practical value as means of transportation for passengers and goods.

Of these two systems, one is identified with the author, and the other is known under the name of the Langen system, and is used to connect the towns of Barmen and Elberfelde, Germany. This paper will more especially describe the development and application of the former system. No claim is made by the author of this paper as the originator of the fundamental principle of the system of monorail railway. It is difficult to trace who first suggested it, as there were several almost simultaneous attempts in that direction between the years of 1875 and 1884. His only claim is to having taken up the original idea in 1884, when it was still in its simplest and most primitive shape; to having developed the general ideas and principles of others in designing the practical details; and to having constructed for the first time, in 1886 for steam power and in 1896 for electricity, monorails which have been worked successfully for the carrying of passengers and goods.

The Behr monorail is applicable to three distinct purposes, namely, to light railways in sparsely populated districts and in hilly countries where they would serve as feeders to existing railways, as elevated railways in towns, and as supplementary to existing systems of mail lines all over the world for carrying express passenger traffic, mails and parcels at much higher speeds and with much greater frequency of trains.

The advantages over ordinary lines in the first of these applications, result principally from the possibility of using very sharp

curves, avoiding the expense of earthworks and tunnels, and also from the smaller cost of bridges, etc. The result of this economy would be about 50 per cent in hilly countries, in comparison with an ordinary meter gauge railway.

The special principle of the Behr monorail was in 1883 applied by Mr. Charles Lartigue in the construction of some primitive

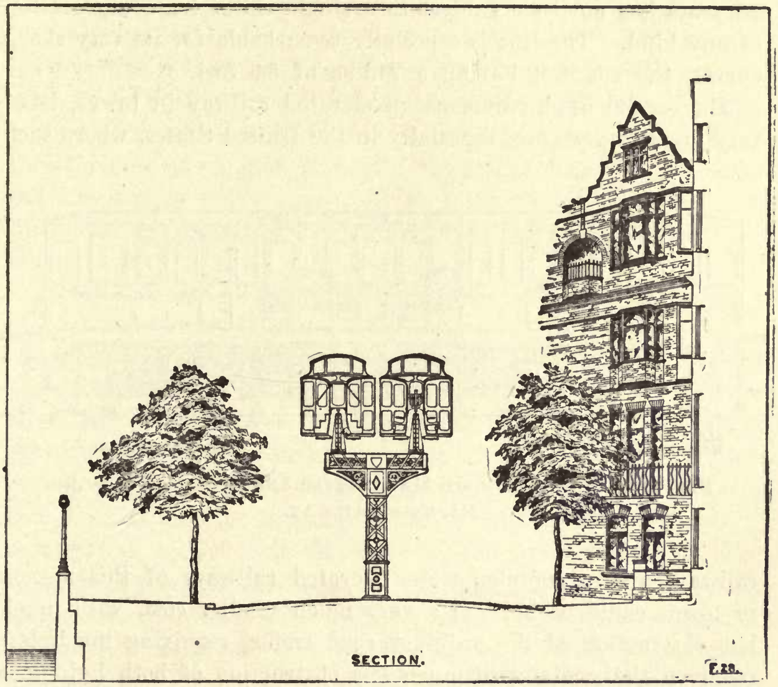


FIG. 1. PROPOSED METROPOLITAN RAILWAY FOR CHELSEA EMBANKMENT, LONDON.

lines in Algeria and Tunis for carrying esparto grass and similar produce, the tractive power being by animals in all cases.

An experimental line was built by the author in London, in the rear of Victoria street, Westminster, in the year 1886, where for the first time locomotives and carriages were run on a monorail. On the section was a gradient of 1 in 10, and for about a year the engine took up this incline, without a rack, one light carriage besides its own weight, showing that the adhesion on this form of railway is considerably greater than on an ordinary two-rail

railway, on which on such an incline an engine is hardly able to pull up its own weight.

An act of Parliament for a railway from Listowel to Ballybunion, in Ireland, for regular passenger and goods traffic, was obtained in July, 1887, and the line was passed by the Board of Trade and opened to the public March 1, 1888. It has been working ever since without any difficulty or accidents, and in over 16 years has not been subject to a single claim for compensation of any kind. The line is especially remarkable for its very sharp curves, the smallest having a radius of 54 feet.

The second application, as an elevated railway in towns, is of very great importance, especially in the United States, where such

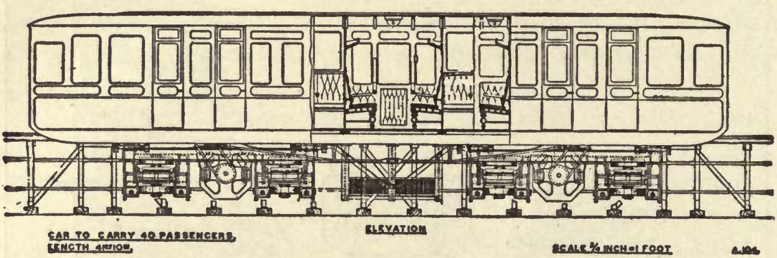


FIG. 2. CAR FOR PROPOSED MANCHESTER AND LIVERPOOL ELECTRIC EXPRESS RAILWAY.

railways are in common use. Elevated railways of this system in towns could be built at a very much smaller cost, with much less obstruction of the ordinary road traffic, requiring much less room on the roads, with much less obstruction of both light and air.

Such a line has been proposed for the Chelsea Embankment, in London, to Putney Bridge. The cost of the line (double track) would be under $200,000 per mile. The system has also been proposed for another metropolitan line in London, about 17 miles long, starting in the west end and going to the city and docks, and nowhere along any street, merely crossing streets. The total cost of this line, double track, is estimated at about $500,000 per mile.

Passing next to the question of high speeds, the great merit of this system for high-speed service is that the cars are absolutely underailable; that it possesses important economic advantages for

working at very high speeds; and that the rise in grade in approaching stations greatly helps the acceleration of the trains when starting and is of equally great assistance in stopping the trains when approaching a station. The cost of construction of such lines is generally slightly less for a speed of 100 to 110 miles an hour than the cost of an ordinary two-rail railway for speeds of 50 to 60 miles an hour.

There are many causes which contribute to the absolute safety of the system which can only be understood by carefully examining the detailed construction of the carriage as it fits to the track, when it will be observed, among other things, that whereas an ordinary railway carriage is held on the rails by a flange of about three-fourths of an inch in depth, the arrangement of the monorail carriage is really equivalent to a continuous flange of over three feet in depth. A feature of great importance to the passenger is that it is not only a safe way of traveling, but it looks also very safe and produces on the mind of the traveler a feeling of absolute security.

On an experimental elevated high-speed monorail built in 1897, with a carriage weighing about 72 tons, a speed of 84 miles per hour was obtained over curves of 1500 ft. radius, and a speed of 70 miles per hour on an ascent of 1 in 90. It was a much greater feat to attain 84 miles an hour on such a line and on such curves, with straight sections so short that it was impossible to construct a proper parabola between them and the curve, than to attain a speed of 110 miles on a properly constructed monorail, under such conditions as would arise in ordinary railway practice.

This line consisted only of embankments about 25 ft. high and cuttings 20 ft. deep, with a total fall of 130 ft. in 1½ miles. The road was built during a very wet winter in a few months, and worked immediately afterwards during a very wet summer, when considerable portions of the embankments had practically been washed away, and many of the sleepers were really suspended in mid-air. Notwithstanding these conditions, experiments were carried out during a period of over twelve months without a single accident. The line was three miles in length, and formed by two short straight lines joined by two curves at each end, so that continuous runs of any length could be made. But as there was a fall of 130 ft., it was necessary to rise to the same level, so that to develop the speed there was practically only a length of about one and one-half miles, and the highest speed

of 84 miles an hour always occurred at the bottom of the incline, at the center of a curve of 1500 ft. radius.

The British Parliament has authorized and the Board of Trade has approved the construction of a monorail between Manchester and Liverpool, on condition that the speed shall not exceed 110 miles an hour. The sharpest curve to which this speed applies has a radius of 1800 ft. The whole of the materials proposed to be used in its construction, above the level of the sleepers, will be of steel. The maintenance will be similar to that on an ordinary railway, as there will be practically no difference in the manner of packing the sleepers or of inspecting the various parts. For the greater security, however, of the workmen employed on the line, the clear space left between two trains passing will be 3 ft., as against 1 ft. 8 in., the space provided between Pullman cars.

All trains will consist of only one car, for reasons of safety, economy in working and construction, and for the convenience of the public. There are three classes of cars designed and approved for this line. The smallest car will carry 40 passengers, the second size 52 and the largest 80. It is proposed to begin the service between Manchester and Liverpool with cars carrying 40 passengers each and running every 10 minutes. The working expenses of this service at 110 miles an hour, including maintenance repairs, management and everything else, are estimated at less than 15 cents per train mile.

The center of gravity of this carriage is at least 12 inches below the top surface of the monorail, as required by the Act of Parliament. The whole working of this line, which will carry, if necessary, 48,000 passengers a day at a speed of 110 miles an hour, doing the whole distance in 20 minutes, is very simple. Collisions are impossible, there are no level crossings, no switches, and notwithstanding the number of passengers carried, there are never more than two carriages on the whole line from end to end.

With regard to the electrical working, full details cannot be given, as the author does not consider that he is especially qualified for that purpose. The joint electrical engineers for the Manchester and Liverpool Railway are Lord Kelvin and Sir W. H. Preece. Following are given, however, some general data:

The distance to be traversed is 34½ miles, without a stop, in 20 minutes. The acceleration at starting is to be 2 ft. per second per

second, diminishing to 9 in. per second per second or an average of $1\frac{1}{2}$ ft. per second per second, attaining a speed of 110 miles in 1 minute 47 seconds and in a distance of under 2 miles. The resistance due to friction and air pressure is taken at 45 lbs. per ton at full speed. The coefficient of adhesion is taken at about one-sixth, say 400 lbs. per ton for the worst weather. The total weight of the car is over 40 tons and the weight of the driving wheels is 20 tons; hence the limit of adhesion that can be calculated on these driving wheels under all circumstances is over 200 lbs. per ton plus 15 lbs. per ton weight for air resistance, giving a total of 215 lbs. per ton weight, being more than the weight required, as 140 lbs. per ton is all that is necessary for an acceleration of 2 ft. per second per second.

For braking purposes, a high-speed Westinghouse brake will be able to retard the train at the rate of 3 ft. per second per second, which will absorb 210 lbs. per ton weight of the car distributed over the four wheels, or $52\frac{1}{2}$ lbs. per ton per wheel. This will stop the car in about 1380 yds. If, in addition to this, the motors are short-circuited, the remaining adhesion can be utilized on the two driving wheels, which amounts to another $52\frac{1}{2}$ lbs. per ton per wheel, and is sufficient for an additional retardation of 1 ft. 6 in. per second per second. This will give a total retardation of 4 ft. 6 in. per second per second, and would stop the car in 768 yds. In this arrangement, the retardation produced by the motors will be at exactly the ratio of the average acceleration to attain the full speed. If the short-circuiting of the motors was used alone without the Westinghouse brake for stopping the train, there would be an available adhesion on the driving wheels of 215 lbs. per ton weight of the car, amply sufficient for a retardation of 3 ft. per second per second, and also for stopping the car in 1380 yds. Therefore, either of the brakes used alone will stop the car in that distance, whereas both combined will stop the car in 768 yds. This does not take into account the steep up grades at the stations.

The power required during acceleration is about 1100 hp, and during the run about 515 hp, or 129 hp per motor, there being four motors to a car.

The generating station is situated exactly half way, at Warrington. Three-phase currents will be generated at 15,000 volts and converted in five sub-stations placed along the line into continuous current at 650 volts. The motors are wound for 600 volts and

weigh each about $2\frac{1}{4}$ tons. The system used is three-wire continuous current.

Each car will be fitted with four continuous current traction motors arranged in pairs. Each motor will have a normal capacity of 160 hp at the full speed of 720 revolutions per minute, but will be capable of giving at least 320 hp for short periods during acceleration. The driving wheels have a diameter of 4 ft. 4 in., the speed at 720 revolutions per minute corresponding to 110 miles an hour.

The whole line will be fenced with an unclimbable fence from end to end, preventing all possibility of trespassing, as there are no level crossings and no means of access of any kind.

By an arrangement on the axles of the guide wheels, which are freely suspended in slots fixed on the bogie or truck frames, the guide wheels on both sides of the car remain always horizontal and in fair contact with the guide rails, whatever may be the inclination of the bogie frames and the car itself, which can swing freely on the top or bearing rail under the influence of centrifugal force in the curves, or from any other causes. The main rail itself remains always perfectly horizontal, even on the sharpest curves. The result is that the pressure on the guide rails need never be increased or the inclination of the car, and this pressure can be limited in such a manner as to combine the greatest comfort of the passengers with the greatest economy in electrical energy through the diminution of friction.

THE ELECTRIFICATION OF STEAM RAILROADS.

BY BION J. ARNOLD.

Eleven years ago this summer it was our privilege to meet under the auspices of a great Exposition, located upon the shores of Lake Michigan, organized not only to commemorate the 400th anniversary of the discovery of this country, but also to direct attention to the advancement made in the various fields of the world's activities, and especially in those arts in which we, as workers, were most interested.

To-day we meet under the auspices of another great Exposition, brought into being to commemorate the 100th anniversary of the peaceful acquirement by the Government of the United States of a large portion of the territory now contained within its borders, to have our attention directed to the development of the various industries of this and other countries that have taken place during the intervening years.

For a few years preceding the former Exposition, engineers and others engaged in electrical pursuits had had their energies absorbed in attempting to show the owners of street railways that operation by electricity was cheaper and better than by means of the horse or the cable. We, at that time, had seen the horse practically disappear from street railway service and the cable supplanted in some instances.

The more ambitious engineers were then advocating the use of electricity on elevated railways, and making figures to prove to the owners of such railways that electricity was cheaper in operation and more desirable for such conditions than steam locomotives, then universally used for such work.

At that Exposition was placed in operation an elevated electric road, known as the Columbian Intramural Railway, which, though the city and South London Underground, a road of light equipment, was started some time before, and the Liverpool Overhead Road soon after, was the first practical commercial application on a large scale of electricity for the propulsion of heavy railway trains.

The success of these roads gave the electric railway industry an impetus which has since resulted in the abandonment of steam and the adoption of electricity on every elevated railway now in operation, and practically on all of the underground roads, thus effectually proving the soundness of the theories of those engineers who pinned their faith to the correctness of the conclusions which their figures showed, and who staked their reputations upon the future to prove them true.

The interval between these Expositions has also been one of great activity and development in the field of interurban railways, which has brought into being the extensive use of the alternating-current, rotary-converter, sub-station system of operating direct-current roads, resulting in the interlinking of thousands of cities with each other and intervening points, thus not only affording a new field for the investment of capital but bringing to most of the inhabitants of the territory through which these roads pass greater facilities for the prosecution of business and the widening of their social life.

With the introduction of the suburban railway came an increased volume of passenger travel, induced by the increased facilities, which may well be noted by the managers of great steam railway properties as an example of what may be expected in increased revenue when frequent and pleasant service is available to the public.

The energies of those engaged in electrical industries have thus far been absorbed in fields which now seem to have been naturally theirs, and their success has been such that they now aspire to enter the field occupied by the steam locomotive as a legitimate field of conquest.

The question now is whether this field is one in which the advantages of electricity will be sufficient to overcome the obstacles which seem almost unsurmountable, and enable it to win as it has in the cases cited.

Those who have given the subject little thought or who are unable to analyze it carefully on account of the lack of the technical knowledge necessary to appreciate the difficulties to be overcome, are most apt to predict the early supremacy of the electrically driven train over the steam locomotive.

That the fields referred to have been apparently formidable yet quickly overcome is not necessarily proof, or even good evi-

dence, that the legitimate field of the steam locomotive can be entered and successfully achieved.

Those most familiar with the subject are now prepared to admit that our great steam railway terminals, where many switching locomotives are shunting back and forth continuously, and those portions of the steam roads entering our great cities, where suburban trains are numerous, frequent and comparatively light, can be more economically operated by electricity than by steam. This is evident to most of those engaged in the work, for the reason that it simply means duplicating, on a large scale, the systems which have proven successful in our street railways, operating, as they do, numerous units running at frequent intervals.

Proof that this field is recognized as a legitimate one for electricity is furnished in the examples of steam railway terminals that are now being equipped electrically, such as the lines of the New York Central and Pennsylvania Railroad Companies in the vicinity of New York, involving an expenditure of something over $70,000,000, where not only suburban service will be operated electrically, but where in the case of the New York Central, the main line trains will be brought into the city from points 30 to 40 miles distant.

While these are great examples of electrical operation on steam railroads, and heroic instances of faith on the part of the railway managers in the ability of electricity to successfully meet the conditions of steam railroad work, where the trains are sufficiently frequent, they are by no means conclusive evidence that electrically propelled trains can be made to successfully meet the conditions of trunk line passengers and freight service, the field now so successfully held by the steam locomotive.

The best conditions for electrical success are a great number of units moving at a practically uniform schedule, at equal intervals, within a limited distance.

The legitimate field of the steam locomotive is now one in which there are few but heavy units moving at uneven speeds over long distances at unequal intervals and at high maximum speeds.

The amount of energy transmitted to any great distance and used by electric cars that have been put in use until recently has been small when compared with the amount of energy that it takes to propel a steam railroad train of five or six hundred tons weight at the speeds ordinarily made by such trains.

It may be taken as axiomatic that when investment is taken

into consideration, power cannot be produced in a steam central station, under conditions that exist to-day, and transmitted any great distance to a single electrically propelled train, requiring from 1000 to 2000 hp to keep it in motion, as cheaply as a steam locomotive, hitched directly in front of the train will produce the power necessary for its propulsion. Therefore, there must be other reasons than the expected economy in power production to warrant the adoption of electricity on a trunk line railroad unless it can be shown that the trains are frequent enough to make the saving in the cost of producing power greater than the increased fixed charges made necessary by the increased investment due to the adoption of electricity.

There are undoubtedly in existence to-day conditions where water power in abundance is available along the right of way of existing roads, in which the substitution of electricity for steam could be made a paying one, with apparatus now available, even on roads having a comparatively infrequent service, but these are special cases and only tend to prove the correctness of the position, for in these special cases the cost of power would be but little over half the present cost of producing it by means of a central steam-driven station.

The ideal conditions for any trunk line railroad having a traffic heavy enough to warrant the investment in a sufficient number of tracks to properly handle this traffic in such a manner as to get the most efficient service out of its rolling stock, would be to have four or more tracks between terminal points, upon which, in pairs, could be run the different classes of service at uniform rates of speed. Thus, if six tracks were used, the through line, passenger, and express service would be run on one pair of tracks; the local passenger, local express, and local freight service upon another pair of tracks; while the through freight service would be run upon a third pair of tracks, and all the trains upon any pair of tracks would run at the same average speed and stop practically at the same places.

If these conditions could prevail and the traffic were sufficient to warrant this investment in tracks, such a service could be operated more economically and more satisfactorily electrically than by steam.

The difficulty is that few roads in existence have sufficient traffic to warrant such an investment in a permanent way, and the result is that all of their traffic must be handled over one or two tracks.

thus necessitating trains of all weights and all speeds running upon the same rails. This results in a tendency to bunch the cars into as few trains as practicable, in order not only to reduce the cost of train service to a minimum but to give the fast-running trains greater headway to allow them to make their time safely. Such an arrangement of trains necessitates the concentration of large amounts of power in single units, which is leading away from the ideal conditions for the application of electricity to the propulsion of trains; and it is this element, combined with the fact that the traffic on most roads is not great enough to warrant the investment necessary in electrical machinery to produce and transmit the power to the distances necessary to keep a few heavy trains in motion, that makes the trunk line railway problem so difficult, as it is more economical to propel these heavy trains by steam-driven locomotives, which are practically portable power-houses.

It being admitted that electricity becomes most economical when a sufficient number of trains are available, and that the steam locomotive is most economical when the trains have become few and heavy, the problem then resolves itself into one of the density of traffic and the question then is: where is the dividing line?

It was my intention to attempt such an analysis of this subject as to be able to formulate some general law which could be readily applied to any given case, and thus enable one to decide whether electrical operation would be more economical than steam in any concrete case.

After carefully analyzing the subject I have become convinced that no general law or formula can be laid down which will apply to all cases, for the reason that the elements entering into different cases vary so greatly that any formula would contain too many variables, dependent upon local conditions, to admit of a general application.

I shall, therefore, only attempt to point out a way in which the dividing line between steam and electricity can be determined after the elements of each case are known.

It will readily be seen that with steam locomotive operation the fixed charges, and cost of fuel and engine labor increase almost directly proportional as the train miles increase, for in this case an additional locomotive means simply a given amount of increased investment, a given amount of increased fuel and labor, and this total investment is least when the number of locomotives is small.

On the other hand, with electricity it is necessary to invest at

once a large amount of capital in the power houses and transmission systems, which amount must be great enough to provide for handling the maximum number of trains required upon the line, and unless this number of trains is great enough so that the economy effected in the different method of producing and applying the power is sufficient to offset the increased fixed charges, due to the additional invested capital, it will *not* pay to equip and operate electrically.

Any problem, therefore, must be analyzed for the relative cost in operation. In case this does not show a saving the advisability of equipping electrically will depend entirely upon the probable increased traffic to be derived from the adoption and operation of electrically propelled trains.

That electricity will be generally used on our main railway terminals, and ultimately on our main through lines for passenger and freight service, I am convinced, but I do not anticipate that it will always be adopted on the grounds of economy in operation; neither do I anticipate that it will come rapidly or through the voluntary acts of the owners of steam railroads, except in special instances.

At first the terminals will be equipped for special reasons, due either to the voluntary act on the part of the terminal companies to effect economy in operation, or to public pressure brought to bear upon the owners through an increased demand on the part of the public for better service, on the grounds that the use of the steam locomotive is objectionable in our great cities.

Those roads which run through populous countries will either build new roads, or acquire, for their own protection, those electric railways already built and operating in competition with them, and utilize them as feeders to their through line steam trains. Thus the steam railroad companies will gradually become interested in electric railways and eventually become practically the real owners of them. With these roads operating as feeders to the main line system and with the terminals thus equipped and the public educated to the advantages of riding in electrically equipped cars, the next step will logically be the electrical equipment of the trunk lines between the cities already having electrical terminals.

Thus some favorably located trunk line having a sufficient density of population will feel warranted in equipping electrically, and when this is once done the other roads running between the

same competing points must, sooner or later, follow in order to hold their passenger traffic.

This may result in temporarily relegating some roads to freight service, so long as they operate exclusively by steam, but with the increased demand on the part of the public for better and cleaner service will come a corresponding increase in passenger revenue to the roads equipped for handling it until one road after another finds it advantageous to furnish an electric passenger service.

With the terminals and main lines equipped electrically, and the desire on the part of the public for more prompt and effective freight service resembling that which is given by the steam roads in England and on the Continent, due to the great density of population, there will be developed a great high-class freight service conducted in light, swiftly moving electric trains which can be quickly divided and distributed over the surface tracks of our smaller cities, or through underground systems similar to that which is now being built in Chicago. Such a system would soon prove indispensable to the public and a source of great profit to the roads as it is now getting to be to many suburban railways.

This class of freight service would soon prove so large a part of the freight traffic of a road that the operation of the through freight traffic by steam locomotives, though at present cheaper, would in time, as the cost of coal increases, grow less, until those roads operating an electric passenger service would ultimately use electricity exclusively.

It has not seemed advisable to me in an address of this character to attempt to furnish detailed figures to support my theories for the subject is of such general interest that many able men are presenting papers upon it at the International Electrical Congress now in session here, in which papers will be found information of much value to those interested, and from which I believe the correctness of some of my assumptions can be proved.

The principal problem before the electric railway engineer to-day is how to make the most effective use of the high-pressure transmission, and high-tension working conductor and maintain safety of operation.

Experiments conducted during the past year by engineers in this country and abroad have made this problem simpler than it seemed before and to-day we seem reasonably certain of the solution.

Until recently the cost of electrically equipping a trunk line under the standard direct-current, rotary-converter system, has been such as to practically prohibit its adoption, but recent developments in the single-phase alternating-current motor field have made it possible to eliminate a large part of the investment heretofore necessary and the prospects for the application of electricity to long-distance running are better than ever before.

When it is recalled that the rotary converter, which was the means of reducing the cost of long-distance roads, was introduced in 1898, and that within the six years from the time of its adoption through the development of the single-phase motor it has been practically rendered obsolete for heavy railroad work, it will be seen that the dividing line between the steam locomotive and the electrically propelled train has moved several points in favor of the latter, due to the reduction which can now be made in first cost and the saving in operating expenses.

With the single-phase motor and the steam-turbine a reality, the transmission problem almost solved, and with the rapid development of the internal combustion engine now taking place, are we, as engineers, not warranted in believing that we can so combine them into a system which will ultimately supplant the steam locomotive in trunk line, passenger and freight service?

I do not anticipate that all roads will soon adopt electricity, for the steam locomotive will hold its field in this country for many years to come, but I do expect, judging somewhat from "positive knowledge," a remarkable development to soon begin in the electrical equipment of favorably located steam roads.

From Richmond, where the first commercial electric road was built, to the present is but 17 years, yet within that time the horse has been relegated to the past as a serious factor in transportation, the cable has served its usefulness and awaits its end, and the suburban railway has been developed and is now rapidly encroaching upon the field of the steam railroad.

With the terminals of the two greatest roads in the United States now being equipped electrically and with an investment of something more than $4,000,000,000 in electrical industries made within a quarter of a century, we have reason to feel satisfied with the past.

With several of the leading roads in this country, of England, of Sweden, of Switzerland, of Italy, and Australia electrically equipping branch lines and seriously considering changing large

portions of their present systems from steam to electricity, we, as personal factors in this great industrial advancement, have every reason to be hopeful for the future.

DISCUSSION.

PRESIDENT ROBERT KAYE GRAY: I do not know whether I am perfectly in order under the American procedure or not, but our habit on the other side, when we receive an address from our President, is to tender him our thanks. As President Arnold has said, during the Paris Exposition we had a joint meeting of the two Institutions, and I am very glad indeed to say that we have in this hall to-day the two gentlemen who presided on that occasion, namely, Mr. Carl Hering and Professor Perry.

I do not think that any one could even have wished to criticise, in any way, the address which has been so ably given by your President, because if any man, either on this side or on the other side of the Atlantic, is pre-eminent in connection with the subject he has treated, I think it is President Arnold. His name is exceedingly well known to us on the other side, and I think I am not giving away any secret in telling you that the evidence of his work which he has been tendering to us has received a very warm reception there, and the evidence is considered to be the best that can be obtained in relation to the matters with which it deals. I therefore wish, in the name of the Institution of Electrical Engineers of Great Britain, to tender to my colleague, President Arnold, our very sincere thanks for his exceedingly able address; and, with your permission, I will ask the senior Past-president of the Institution of Electrical Engineers of Great Britain to second the motion—Colonel Crompton.

COLONEL R. E. B. CROMPTON: It is with the most heartfelt pleasure that I rise to second the motion of President Gray, that the thanks of the American Institute of Electrical Engineers, as well as our own Institution of England, be given to President Arnold for his address, which I personally feel is worthy of this great occasion—the meeting of the two Institutions.

PRESIDENT GRAY: I presume it is unnecessary to put this motion to the meeting, and I shall put it by acclamation if it meets your approval.

PRESIDENT BION J. ARNOLD: I assure you that your expression of approval is very much appreciated indeed.

We have for our discussion this morning a subject similar to that which I have treated in my address; in fact the address was written as a sort of introduction to the discussion of the subject entitled "Different Methods and Systems of Using Alternating Current in Electric Railway Motors." This subject has received the attention of engineers interested in electric railways for the past three or four years. During the past two years it has received very energetic attention on the part of leading engineers of Europe and this country, and it bids fair to be one of far greater importance as we get more thoroughly into heavy railway work. Since I have talked to you quite a while, notwithstanding the fact that my name appears first on the program to discuss the question, I am going to ask a gentleman to open the discussion who is one of the most distinguished engineers in this country, and one of the most distinguished living authorities in electrical matters. I have the pleasure of introducing Dr. C. P. Steinmetz, of the General

Electric Co. and Past-president of the American Institute of Electrical Engineers.

DR. C. P. STEINMETZ: The problem which we have before us here for discussion—the problem of the direct application of alternating currents to electric railways—is not a new one, but it has become of primary importance and interest in the last few years. The early pioneers in electric rail roading, 10 or 15 years ago, started the development of the alternating-current railway motor, and prominently among them I may mention Mr. R. Eickemeyer and Mr. VanJepoele, who designed alternating motors for railway purposes and investigated their characteristics. However, very little progress was made in this field for many years, for a number of reasons; one being that in those early days frequencies of 125 to 130 cycles were customary, far higher than we are using now and the difficulties of the problem were thereby increased so formidably that advance was necessarily very slow. In addition the very rapid development of the direct-current railway motor fully occupied the attention of all electrical engineers, and therefore the less urgent field of the alternating-current motor was necessarily somewhat sidetracked. Then the alternating-current polyphase induction motor came into the foreground, showed its superiority over other types of motors for stationary work, and impressed the engineers to such an extent that for a long time it overshadowed the work done by the early investigators on the variable-speed alternating-current motor, that is, on motors with series characteristic. Attempts then were made to introduce this very successful polyphase induction motor into electric railway work, attempts which have not been successful to any great extent. In the meantime, in the United States the synchronous converter was developed and became a standard piece of apparatus familiar to everybody—standard as much as the direct-current generator and the alternating-current generator, and experience with such synchronous converters shows that for electric railway work, for the violently fluctuating loads on the railway system, the synchronous converter is superior even to the direct-current generator: the absence of armature reaction, the phase control of pressure feasible in the converter, and corresponding close pressure regulation makes it specially able to withstand and take care of very violent fluctuations of load and to carry overloads which no direct-current generator can carry. This apparatus became standard, and with its introduction the field of the direct-current railway motor—the distances which could be covered by the direct-current railway—was extended practically without limit, and a field opened which has been exploited in the last years, which was the field dreamed of by the early pioneers; the difficulties, however, being overcome, not by the development of the alternating-current motor, but by the development of methods of transmitting alternating currents and transforming them into direct currents along the routes, in synchronous converter sub-stations.

Now, however, in the last year or two, with the still further development of the electric railway we have approached and in many instances reached the limits of applicability of this synchronous converter. The synchronous converter is a piece of machinery which requires sub-stations, requires some attendance, and as a necessary result has a high economical efficiency only

where the traffic is sufficiently condensed to warrant the maintenance of sub-stations within relatively short distances from each other. Where the number of trains is less or the power per train greater than can be supplied at 500 volts from sub-stations, without excessive expenditure in line conductors, and too excessive fluctuations of load, pressures are required higher than can be utilized efficiently in direct-current motors, and there we strike the limit of the synchronous converter, and the alternating-current motor has to come in.

Personally I do not believe that the alternating-current motor will make very serious inroads in the field now occupied by the direct-current railway motor. I do not believe that direct-current railway systems will be changed into alternating-current railway systems; but what I expect of the alternating-current railway motor is that it will find a field of its own, a new field; just as when the alternating-current method of distribution was developed in this country, it did not displace the direct-current method of distribution which occupied the centers of our large cities, but it found a field of its own, a field which has gradually developed so as to be equal in importance if not superior to the field occupied by the direct current. Hence, to conclude these remarks, what I expect of the alternating-current railway motor is that it will find and develop a field of its own, that field which the direct-current railway motor cannot reach—suburban and interurban service, long-distance service, secondary railway service.

When considering the technical aspect of the subject before us for discussion to-day, the relative advantages and disadvantages of the direct- and alternating-current railway motors, we have to consider, first, the character of the problem we have to meet in electric propulsion; secondly, the character of the apparatus which we have available to solve these problems; thirdly, the additional features imposed upon the problem, or conditions more or less outside of the problem, as, for instance, the condition of the electrical industry at present, the existing investment in direct-current and in steam railroads, which have to be taken into consideration when discussing any new system of railway propulsion.

Regarding the characteristics of the different types of motors—the direct-current series motor now in universal use for railroad work, the polyphase induction motor proposed, and, to a certain extent, tried in recent years for railway work, a motor eminently successful in stationary work—and the alternating-current single-phase railway motor with commutator, I have in a paper before the International Electrical Congress given the results of a theoretical investigation and discussion of these different motors and shown the speed-torque curves, or characteristic curves of these motors in relation to each other. In Fig. 1 is given a comparison of the typical speed-torque curves of the different types of motors.

In general, the characteristic of the polyphase induction motor is essentially that of a constant-speed motor, with shunt-motor characteristics; that is, it can efficiently operate over a certain limited range of speed only, cannot exceed the synchronous speed, and when operating below its normal speed, it operates less efficiently; that is, when operating at a lower speed than normal, or approximately synchronous as can be done by a rheostat in the secondary circuit, the polyphase induction motor merely wastes that

part of the power corresponding to the difference between its actual speed and synchronous speed. Or, in other words, at low speed the induction motor consumes the same power which it consumes with the same torque at full speed, though its power output is reduced in proportion to the speed, and its efficiency correspondingly.

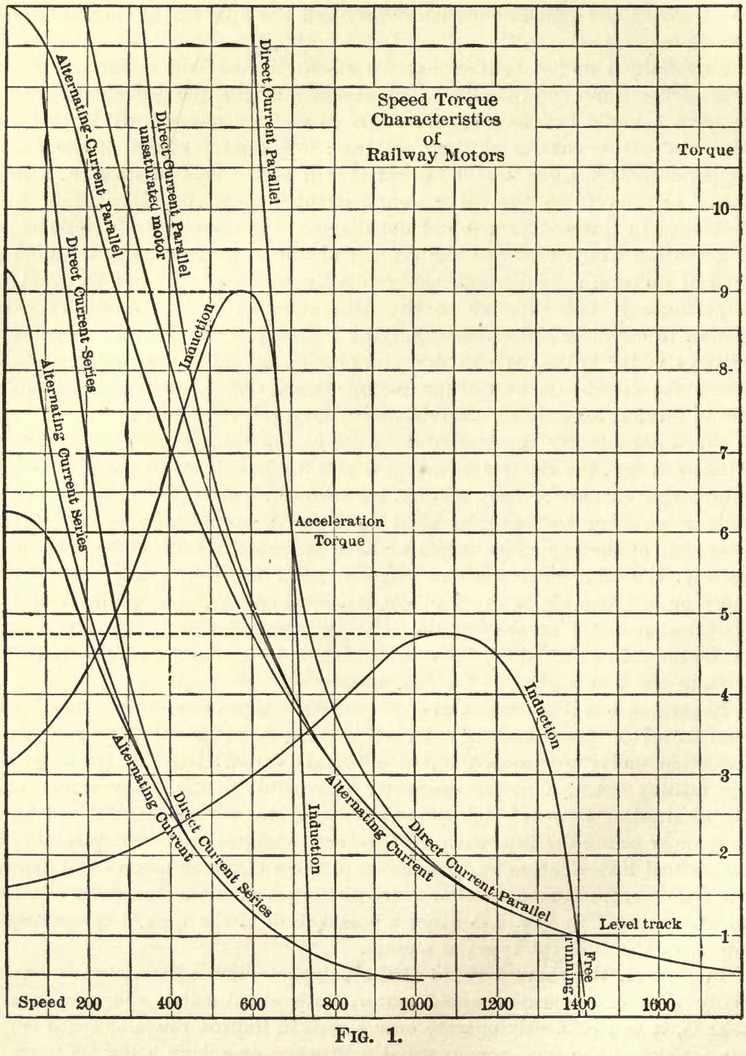


FIG. 1.

In the direct-current series motor the torque developed by the motor decreases with increase of speed, and inversely with increasing load the speed of the motor decreases. The maximum torque of such a motor occurs in

starting. All variable-speed commutator motors, alternating and direct, more or less differ from each other in the rate at which the torque varies with the speed, and that brings us to a consideration of the requirements of electric propulsion.

Important classes of work to which an electric motor may be put in locomotion are: first, city railway or tram car work; secondly, rapid transit service as on elevated and underground roads; thirdly, suburban and interurban service; fourthly, trunk line passenger service; fifthly, long distance freight service, and sixthly, elevator service.

Now, discussing these briefly in succession. The city tram car service is characterized by its frequent stops of irregular duration, at irregular intervals. To maintain good average speed it is therefore essential that the motor should get under way after the stop as rapidly as possible; that is, have a very high starting torque and accelerating torque, and carry this high torque up to a considerable speed. Beyond this speed, then, the torque of the motor should decrease fairly rapidly down to the torque required to run on a level track, which we may assume roughly to be at twice the speed to which the high torque of acceleration should be maintained. In addition thereto, it is necessary that the motor should accelerate efficiently and that it should be able to operate efficiently at low speeds in those city districts where the general traffic is dense and where it is not possible to run at high speeds. The characteristics of this type of motor are pre-eminently given by the direct-current series motor. If we assume the torque required to run on a level track as 1, probably the starting or accelerating torque may be something like six times as high. At that torque we start and run up to considerable speed, and then strike what is called the *motor curve* and after cutting out all regulating devices, accelerate with decreasing velocity up to the free-running speed. Such a curve, that of a typical direct-current railway motor, is given in Fig. 1, marked "direct-current parallel" and "direct-current series." The induction motor, although it may accelerate with a high torque, at the end of acceleration, the speed is limited. It accelerates up to or near synchronous speed, and there the torque falls off to zero; and hence that part of the torque curve which is so essential to city tramway work, the curve of running with decreasing torque, from the limit of acceleration to the free-running speed, does not exist in the induction motor. We can indeed reach the free-running speed of a direct-current motor with a polyphase induction motor by gearing it to twice the speed, making synchronism the free-running speed, but this means that the available torque of acceleration, and therefore the rate of getting under way, is reduced by one-half, or, if we make it the same, the motor capacity is twice as great, requiring a motor twice as large. Considering that in this service a very considerable part of the running time is occupied running on approximately level track with torque very small compared with the accelerating torque, we see that the highest possible efficiency of the motor at light load is essential. Here, however, is the place where the induction motor falls down. A polyphase induction motor running at, say, one-tenth of its maximum output runs very uneconomically and with very poor power-factor. So in the polyphase induction motor, when used for railway service, you cannot combine very high acceleration with high efficiency in

free running, and with the ability of running efficiently at low speeds, as you can in the direct-current series motor with series-parallel control. Therefore, the induction motor is not suitable to the class of work which we call city service or tram-car work.

The alternating-current commutator motor of which two sets of curves are shown in Fig. 1, marked "alternating-current parallel" and "alternating-current series" has characteristics very closely similar to the direct-current railway motor, except that possibly the variation of torque with the speed is less. That means, with the same decrease of speed the torque does not increase at the same rate as with the direct-current motor; if we assume again the same free-running torque as 1, and the torque of acceleration six times the free-running torque, the direct-current series motor will carry the acceleration torque up to half speed; the alternating-current motor not quite as high. This means with the same maximum acceleration you will strike the motor curve at a lower speed, accelerating on the motor curve, you get under way, then, slightly slower, or to get the same average acceleration you have to start with a higher maximum acceleration. Now, this is an advantage in some cases in so far as you run for a longer period of time and over a wider range of speed on the motor curve, that is without controlling devices, hence in the most efficient manner possible, and thereby make up to a considerable extent for that power which the alternating-current motor inherently loses by its slightly lower efficiency due to the alternating character of the magnetic field, and the losses by magnetic hysteresis in the motor field of the alternating-current motor which do not exist in the direct-current motor. This difference in the speed-torque curve of the alternating-current series motor, compared with the direct-current series motor, is due to the lower magnetic density used in the alternating-motor field, and, at low speeds, also to the e.m.f. of self-induction. The first phenomenon, therefore, also occurs in an unsaturated direct-current series motor (Fig. 1), and such a direct-current series motor therefore has at high and medium speeds the same characteristics as the alternating-current motor. It is undoubtedly true that alternating-current motors can be designed to give very closely the same characteristics as the standard direct-current series motor. However, the motor as it is before us at present reaches the motor curve at a lower speed, therefore with the same maximum acceleration, gives a lower average acceleration up to full speed, or with the same average acceleration requires slightly higher maximum acceleration.

Coming now to the second class of service, rapid transit service, here the problem and the conditions of operation are almost identically the same as in city service, except that the units are larger, the speeds are higher, the stops not as frequent, absolutely, but about just as frequent relatively in comparison to the maximum speed of the motor, so that we can directly apply our considerations to rapid transit service—regarding a comparison of polyphase induction motors of alternating-current commutator motors, and of direct-current motors.

In interurban and suburban work, that is, in railroads running out from the cities far across the country into the suburbs or into other cities, we have a much lesser frequency of stops. That means that rapidity of acceleration is of lesser importance, and we can well get along with a lesser average

torque of acceleration, but we must have the same surplus torque as on city service work, or rather a greater surplus torque, because, while in city service and in rapid transit service, where the distances are relatively short, we can count on maintaining fairly constant pressure in the supply system, we cannot to the same extent count on this in interurban and suburban service where we are far away across the country, except by investing much greater sums in line conductors and feeders than is commonly economically desirable or feasible. Hence, in this service the motor should have a greater surplus torque than in city service, so as to get a sufficient margin to start the train or the car under the most severe conditions on an upgrade or an overload, even if the pressure in the system is low. The motor which is most sensitive to pressure variation is the polyphase induction motor. The maximum torque which this motor can give necessarily cannot very much exceed the acceleration torque without badly spoiling the characteristics of the motor either electrically or mechanically; but the maximum torque varies with the square of the pressure and hence rapidly decreases if the pressure of the system is low. In the motors with series characteristics, however, like the single-phase commutator motor, the direct-current series motor, the torque does not depend on the pressure, or rather, while the maximum torque so depends, the theoretical maximum torque which you get from the motor when standing still is so far in excess of the torque of self-destruction, or rather of slipping the car wheels, that it is not reached, and the effect of variation in the supply pressure is merely a variation in the motor speed. That is, if the pressure is low in the system, the direct-current motor and the alternating-current commutator motor run at lower speeds, but still are able to give the same torque, while the polyphase induction motor runs at the same speed, but is not able to give the same margin of torque, and at a certain load falls down or does not start. That means that in designing a system of transmission and distribution for alternating-current commutator motors or direct-current motors we are permitted to design the system for the average drop of pressure in the system while in designing it for induction motor service, we have to take into consideration the maximum drop of pressure in the system which is very much greater that the average.

For interurban and suburban service we require an excess overload in torque, but do not require an acceleration up to high speed. The alternating-current commutator motor appears to be preeminently satisfactory in this work, and there is where I believe it will be used extensively, and where the advantage of a high-pressure trolley and of the absence of substations is specially important.

In trunk line passenger service the rate of acceleration as given at present by the steam locomotive is very much less than every-day practice in electric railway service. So here we do not need this excess acceleration torque sustained up to high speeds. Here, again, we find a field where we may apply the alternating-current commutator motors. The polyphase induction motors could be used if the question of pressure supply did not come in, as I discussed above, and if furthermore the limit in speed of the induction motor was not so objectionable in passenger trunk service, where, more than anywhere else, we desire to get the full benefit of the track by running at

the highest safe speeds wherever the track is level. This the induction motor with its limited speed cannot do.

In trunk line freight service, the same considerations come in, except there the speeds are relatively low, the train weights great; and it is more than anywhere essential to have a very large surplus torque available to get under way or to hold the train on a grade. You must, therefore, in this class of service, just as in suburban and interurban service, have a motor running efficiently at light load, but being able to give very high torque, although it does not need to carry this torque up to high speeds. On the contrary, it is not desirable in freight service that the motor should sustain a high torque up to high speeds, because that would mean the consumption of very large power. In freight service the highest possible economy is especially necessary, and the highest possible economy means the least fluctuations of power consumption; that means on up-grades you would desire to go slowly and reduce the power consumption and get the high speeds on the level track.

In mountain railways and such classes of work, the running torque is of the same magnitude as the starting torque, and so the load on the motor is more nearly constant than in any other class of railway work, and on the down-grade the motor is preferably used for braking, by returning power into the line. Here then the polyphase induction motor appears well suited, and is indeed being used successfully. Such service, however, is in its character more nearly akin to elevator service than to railway service.

In the discussion so far I have considered the requirements of the different classes of railway service, irrespective of extraneous conditions. When considering the alternating-current motor and the direct-current motor, we have to take in view what exists at the present time in this country and abroad. There exists the enormous network of steam railroad and of direct-current electric railways. The steam locomotive is a unit of very high efficiency, but a very large unit. It therefore for efficient operation requires the massing of traffic in heavy trains, and results in less frequent but large trains. This has practically rearranged and reorganized the whole system of locomotion by collecting it into a small number of very large units. That is not the most efficient manner of operating electrically propelled vehicles, but rather the contrary. Furthermore, you have to consider that every city and almost every village has a direct-current railway system. Now, the main and most important features by which the electric railway motor and electric propulsion has gained and is gaining rapidly in competition with the steam locomotive, appears to me to be the frequency of headway and the absence of passenger stations, not the speed, which frequently in electric lines is lower than that on steam railroads paralleled by them. The electric railway picks up its passengers anywhere in the city and deposits them anywhere and it does not require them to consult time tables, but runs its cars so frequently that the passenger can always find a car within a few minutes at any point; on the other hand, the steam locomotive requires you to consult a time table and go to a depot. As soon as the electric railway gives up this advantage which I have just mentioned, I believe one of the main advantages of the electric railway over the steam railroad will be lost, and this, therefore, is the feature which has to be kept

in view. It means that whatever type of motor may be adopted in interurban or suburban service, etc., it must be able to carry the passengers through the cities over existing railways.

The existing railways are direct-current railways, and I believe will remain so. That means that the long-distance motor, at least the suburban and interurban motor, must be able to run over the direct-current system. Hence, it must be a type of motor equally applicable and capable of operation on a high-pressure alternating-current or on the 500 volt direct-current system.

Taking this for granted the methods of control must also be as simple as possible; that is, the same control for alternating as for direct current. Even if the motor could be used on direct current and alternating current, if we would have to carry a double system of control, one for city service and direct current, the other for long-distance service and alternating current, this would be a very serious handicap. It means that really to solve the problem before us, of extending the electric railway into interurban and suburban service, and into the field now occupied by the steam railroad systems, and into new fields not yet developed, to a large extent not even dreamed of, that we must have a motor which with the same controlling appliances and the same characteristics, can run either on the high-pressure alternating circuits or on the existing direct-current circuits.

Furthermore, the enormous investment in electric railway systems existing at present has all been made, in the large systems, on 25-cycle, three-phase apparatus. That means that we shall have to continue to operate at 25 cycles. It may be preferable, possibly, to run at lower frequencies, or it may be preferable to run at higher frequency in this instance or that instance, but regardless of whether it is preferable or not, if it can be done on 25 cycles, it will have to be done on 25 cycles, and if another frequency had to be used, it would be a very severe handicap to the new system. I am glad to say that there is no doubt that 25 cycles is the frequency best suited to the alternating-current single-phase railway motor.

President Gray: Dr. Steinmetz' remarks have been so clearly stated and so closely reasoned out that they do not give us much chance for discussion, but I am glad to refer to my English colleague, Professor John Perry, upon whom I call to take part in this discussion.

Professor John Perry: I have to confess that I am not prepared to take part in the discussion. We have had the address of President Arnold and this excellent address of Professor Steinmetz, and two such addresses in one morning I think we have never had before. Clearly, they are men who have thoroughly studied the subject, and in view of what they have said, I think what it comes to is this—that everything seems to depend to a very great extent as to what is to occur in connection with the electrification of steam railroads in the next ten years, on the success of the single-phase alternating-current motor. I knew of the progress that had been made by the General Electric Company and the Westinghouse Company, I had heard a great deal about it before leaving the other side, and it is one of the things that I promised myself to learn something about during my visit here. I have not yet been able to do much in the way of getting accurate knowledge on the subject. I have been on a tram-car at Schenectady, the motor of which,

I was informed, was driven by direct current and the car ran well; and then I would get on another car, and I was told that the motor was driven by alternating current, and it seemed to run just as well, so that I was not able to acquire any knowledge. I had no means of experimenting or ascertaining what the efficiency of the various arrangements were. Some 10 or 12 years ago I was tremendously interested in the single-phase alternating-current motor, perhaps for a selfish interest, as I had invented a system of traction which required the use of that system. I suppose we are all tremendously interested in this thing, and are all anxious to learn what we can about the alternating-current motor. I wanted to go to the section in which Mr. Steinmetz was giving an account of the work yesterday, but I was told it was my duty to attend a discussion upon the subject of electromagnetic units in another section, and as a man cannot be in two places at once, I had to attend to my duty as it was pointed out to me. In these circumstances, I can only say that I should like to hear the discussion of this subject proceed further before I shall feel able to take any part in it.

President Arnold: It has been said that the fame of a scientific man is a quiet fame, but that is the most satisfactory after all. It does not attract the multitude. A man is able to walk in a crowd without being pointed out, which by the way, is a very satisfactory thing to do; but he finds that when he reaches different parts of the world his name has preceded him in the circles in which he moves, so that he after all enjoys in the most satisfactory way the results of his efforts in the particular line of work which he has been following. We have many such men present to-day, and among them is one who has done excellent work in the special line we are discussing this morning. I shall now call upon one of our distinguished engineers and colleagues, Mr. B. G. Lamme, of the Westinghouse Electric & Manufacturing Co., of Pittsburg, to discuss the question further.

Mr. B. G. Lamme: Away back in the dark ages of electric traction, about 15 years ago, there was great confusion in the types of apparatus used. There were all kinds of motors and all kinds of apparatus on the car. They only had one property in common—they were all direct-current. After putting a number of these systems into commercial use it was discovered that certain types of apparatus were superior to others, and those particularly interested in the manufacture of such apparatus followed up this matter to ascertain what properties were of the greatest value. It was gradually discovered that one type of motor was taking precedence of all others, namely, the series motor. Practically all development for a certain time was in the direction of the direct-current series motor.

The reasons which led to this were partly based on theory and partly on practice. The series motor gave the effect of a cushion on a car. The motor is inherently a variable-speed machine and automatically varies its speed with the condition of the load. That was discovered to be a matter of first importance in the smooth operation of electric cars. Also the motor automatically increases its torque in a greater proportion than the current, which is of great importance in regard to starting and acceleration. These points were possibly not as well understood at that time as at present, but experience showed that certain equipments were superior to others and development was along that line.

After a few years, when the motors had reached standard proportions and practically but one type was used, a second limitation was discovered; namely, in the transmission conditions. It was found that in the extension of the railway system, the ordinary 550- or 600-volt direct-current system was becoming cumbersome, and it was evident that some method of transmitting power at higher pressure and transforming to lower pressure for utilization would be necessary. The most evident method was naturally to transmit by alternating current and convert to direct current, in order to use existing car equipment. This led to the use of motor-generators, and later to synchronous converters.

The motor-generator was found to fit the existing alternating system fairly well, but in the development of the synchronous converter the manufacturers discovered a great difficulty in existing systems. The frequencies of 125 and 133, which were the standards for many plants, were entirely unsuited for synchronous converters and also not well adapted for synchronous motors. Another frequency, coming into general use, namely, 60 cycles, was found to be possible for use with synchronous converters, but the difficulties of design were very great in that case, and the synchronous converters were rather heavy and cumbersome.

At that time there was fortunately a new frequency adopted which was of prime importance in the development of the synchronous converter, namely, 25 cycles. So far as I know, the origin of that on a large scale, was as follows: in the Niagara Falls power plant, when it was first laid out, the engineers for the power company had arranged for a frequency of 2000 alternations per minute, or 16⅔ cycles per second. They wished to use 8-pole machines, running at 250 revolutions. The company which I represent, which was one of the prominent bidders on the contract, objected seriously to the proposed frequency, as it was considered entirely uncommercial and also not suited for the best design of machine. The engineers of this company recommended 4000 alternations per minute or 33⅓ cycles per second. That was considered extremely low compared with anything then in use. As we could not come to any agreement to use that frequency, we finally compromised on 3000 alternations per minute, or 25 cycles per second, and the first Niagara machines were built in that way. There were various reasons for the adoption of a low frequency, one of which was that commutator type of motors might possibly come into use. Another reason was that it was better adapted to synchronous converters, but it was admitted that 33⅓ cycles would also be satisfactory.

After the Niagara Falls plant was installed, there was then a precedent for the adoption of this frequency for large units, and the manufacturers began to build apparatus of this frequency for the Niagara Falls plant and also adopted it for other plants. This opened quite a field for the synchronous converter and it soon began to be extensively used for railway work, as it was recognized that this was the link needed for extending the direct-current system. Even at the early date of 1893 and 1894 it was believed by many engineers that the synchronous converter was simply a machine to meet an emergency condition, that it would not last, that the time would come when synchronous converters would be dropped from the railway service, but as the most convenient and apparently the best solution of the

problem, it was adopted extensively. About that time electric railway service began to be greatly extended and synchronous converters have thus come into very general use. By the use of synchronous converters, the advantages of the alternating-current system in transmission are obtained and the advantages of the direct-current system with the series motor are retained. Distances could be extended indefinitely by increasing the number of synchronous converter stations and raising the pressure of the alternating-current lines.

Shortly after this system came into general use it was recognized that a purely alternating-current system, in which purely alternating current was supplied to the motors, would be advantageous and considerable work was done along that line. The polyphase motor apparently had the field, and naturally the manufacturing companies took up the question of the application of the polyphase motor to traction work. The company which I represent, the Westinghouse Electric & Manufacturing Company, took up this question in an active way about 1895, and built two motors of 75 hp each for traction work. These motors were equipped with collector rings and rheostatic control and tests were made in regard to performance, both with straight rheostatic control and with the new well-known "tandem" control, in which the secondary of one motor is connected to the primary of the other to obtain half-speed conditions. Even with this latter arrangement it was found that the motors would not compare at all favorably with the direct-current motor or the system with the direct-current system using rotary converters, and this work was abandoned. It was recognized that the polyphase motor did not possess the proper series characteristics which long experience had shown to be so necessary for railway work. Other experiments along this line were made, using polyphase motors wound for two or more speeds, and two 100-hp motors were built which were wound for several speeds. While this was better than the other arrangements, it still appeared that this was not a solution of the problem. Previous to this time the company had done some work in the direction of using single phase, but not as a solution of the problem which presented itself in 1895 and later.

In 1892 the question of the use of the commutator type alternating-current motor for railway work was taken up. Two motors of nominally 10 hp each were designed and built. These were built for a frequency of 2000 alternations per minute, or 16⅔ cycles per second. They were mounted on a car and were operated for awhile, but the system was not a success. In the first place the pressure used—400 volts as compared with 550 in the direct-current motor—was rather low. It was considered that as 550 volts was the limit in the direct-current motor, 400 volts would be the limit with alternating current. The motors were tested on a track of iron rails with practically no bonding. The track drops were excessive and the pressure fluctuations were great. The generator used—of about 20 kw capacity—was entirely too small for this work and it was not adapted to handle the inductive loads which were found with alternating-current motors. A series of tests was run and it was finally decided that for city work, for which the system was then laid out, the motor could not compete with the direct-current motor. It was decided, however, that such a type of motor

would probably furnish the solution of the heavy railroad problem, but as there was no such heavy railroad problem at that time, the work was dropped for awhile. But in 1897 the question of the use of the commutator type of alternating-current motor was again taken up—this time on a somewhat larger scale. Motors of 50 hp were built for variable-speed work, and given a long series of tests. Then after sufficient experience had been obtained, the work was gradually carried to the larger sizes.

In 1900 and 1901, when the question of the polyphase traction in Europe was so extensively advertised, it became evident that there was actually a demand for an alternating-current railway system. It was therefore decided to continue the previous work with large motors of the commutator type, and two motors of 100 hp were designed and built. For these also, the frequency adopted was 2000 alternations per minute, or 16⅔ cycles per second. This fractional figure was primarily adopted on account of certain steam-engine conditions. It was recognized that an even frequency of 16 or 18 would have been practically as good.

In the earlier work, with the 10-hp motors at the low frequency, it was recognized that it would be absurd to put such a system on the market, as at that time even 25 cycles had not been adopted. The frequencies in common use were 50 or 60 and a drop to 16 cycles was considered prohibitive. In the latter work, as 25 cycles had come into general use, and 15 or 20 cycles had been talked of and proposed by certain companies, it was considered that in view of their advantages for railway work such frequencies should be adopted. The motors were hence built for the above frequency. The results obtained with these large motors were so satisfactory that a contract was taken for a rather large road and the apparatus prepared. Knowing that news of this would soon be abroad, it was decided that the matter should be brought before the American Institute of Electrical Engineers, and a paper was presented on the 26th of September—two years ago—which I believe was the first announcement of the application of the single-phase alternating current to railway motors. There was considerable discussion—mostly criticism—and it was generally considered by the engineering public that the weak point of the system was the commutation. At the present time, however, I believe this is no longer considered as a serious point.

Previous to building the 100-hp motors we had had considerable experience with the commutation of such motors. Besides a long series of tests, we had run 40-hp motors at practically full load on a 60-cycle system for nine months, day and night. At the end of the nine months the commutators were in practically as good condition as in the beginning, showing that the commutator on such machines could be made to have a long life. The conditions of the 60-cycle machines were much worse than on the lower frequency, and the nine months of operation under the condition of steady service probably equalled two or three years of traction service; but the commutator stood up so well that we decided definitely that there was no difficulty on that point.

The principal reasons which led to the adoption of the single-phase motor were stated in the paper above referred to, and were that but one trolley wire would be required and that the motors had the series characteristics.

It was considered that no motor, except one of the commutator type would give suitable characteristics for the service, and it was stated that there were several types of motors, with commutators, which had the proper characteristics. All of these may be classed as series motors, although some of them are combined with transformers and may be considered as transformer series motors, or, under another name, as repulsive motors, and others are pure series motors. The pure series motor is one which can operate on direct current as well as alternating current. The repulsion motor can be modified so as to operate on direct current, but as ordinarily arranged it is not as well adapted for this as the other type. It was recognized in the first undertakings with this system that the motor would probably be required to operate on direct current at times, and the fact that the pure series motor was primarily a direct-current motor of a first-class design was one of the reasons which led us toward the adoption of that type. As both theory and experience indicated that such motors would probably be wound for 200 or 250 volts, it was recognized that the motors would probably have to be operated in series for direct current, and either in series or in parallel for alternating current as might be desired. The arrangement required for permitting operation on direct current as well as alternating are rather complicated, due to the fact that it is necessary to switch from one system to the other in passing from the alternating to the direct current. We did not suppose that the electrical public would consent to such a combination, but since that time we have found that in some instances they do not object seriously to the increased complication.

At the time that the alternating-current system was brought out it was considered that the principal field would be in heavy railway work, because this motor furnished what was considered a general solution of the railway problem; as the railways would have their own terminals and their own rights of way, the system would be an alternating-current system throughout. At the present time, however, roads are being installed which operate primarily on alternating current, but at the terminals and where they pass through intervening towns they operate on direct current.

The direct-current motor has never been considered as entirely suitable for the heavy railway problem, as usually but two speeds, and at most but three speeds can be obtained with four motors, the third speed increasing the complication considerably. With the alternating-current motor of the commutator type any speed can be obtained for locomotive work, because any pressure can be applied to the terminals of the motor. As soon as alternating current is used for motors, we at once have a ready means of pressure transformation. As on locomotives for large capacity the difficulty of handling the current is considered a very prominent one, it was considered that some form of pressure control which varied the pressure without opening the circuit would probably be the best one. One form of pressure control permissible is what is called the induction regulator. This regulator varies the pressure without opening the circuit. The relation of the primary and secondary windings with respect to each other is varied. This gives a means of varying the pressure to the motors and varying the speed of very large motors with no tendency to sparking at the controller. The only time the circuit is opened is at the end of the operation when

cutting it off. Therefore it was considered as an important feature in the solution of the general railway problem.

The single-phase system is the one means presented at the present time as the solution of the heavy railway problem. It has all the advantages of the direct-current motor in the variable-speed characteristic, and has also the advantage possessed by alternating current in the ability to use any line pressure desired, and to vary the pressure applied to the motor and thus vary the speed over any range desired. It also has the advantage of permitting a system of control that can be obtained without sparking.

In the adaptation of the alternating-current motor to direct-current service, two 250-volt motors can be connected in series for 500 volts; also in operating on alternating current the motors can be connected in series, if desired, or in parallel. There is a possibility of danger in operating two motors in series in this way on alternating current, or even on ordinary direct current. In ordinary direct-current practice the use of two motors in series for part of the service is common practice, but there is this difference between the direct-current equipment and the alternating-current equipment. In the direct current we have motors wound normally for 500 or 600 volts. When operating in series the motors are connected, two in series, each one receiving 250 volts. Therefore, if one motor should slip its wheels and take the full pressure of the pair, it would still be operating at its normal pressure. But with two 250-volt motors connected across a 500-volt circuit, we have a different condition. In case one motor should take the entire pressure, we should have 500 volts across a 250-volt motor. That condition was considered early, and in the Washington, Baltimore, Annapolis project, a description of which was given in the American Institure paper read two years ago, we showed an arrangement by which this could be avoided. We had balancing transformers connected across the two motors in series. The balancing transformer was across the outside terminals, and a tap from the middle of the transformer was connected between the two motors. In this way equal pressure was supplied to the two motors in series, and the danger of a runaway was thus avoided. It is not yet determined how important this is, but I believe that something like this will be found advisable for the operation of motors in series, especially where high-power motors are used on medium weight cars for high-speed service. Possibly with comparatively low speed, and with very heavy cars, there may not be the same tendency to slip. On the direct-current part of the road, of course, the balancing transformer could not have any effect; but as the direct current is usually a very small part of the service, this danger would be lessened, due to the proportionate time in service.

In the application of the motor to use on both alternating and direct current, we have found some special conditions which affect the arrangement of control. Take, for instance, a large road being installed between Cincinnati and Indianapolis, where it is intended to run on direct current at the terminals and alternating current on the rest of the line. The normal speed on the alternating current part of the line is so great that it would be prohibited in the towns, and it is found that to get the speed down to the desired rate in the city service on the direct-current portion of the road,

it is necessary to connect the four motors all in series, and thus no series-parallel arrangement can be used. Pure rheostatic control is therefore necessary in the city. On the suburban part, a switch is used to throw the current from direct to alternating, simply throwing the four motors in parallel, and taps are used on the lowering transformers to get a number of pressures. In that way we get the effect of series-parallel control and even better, by having more than two steps. On a long line it is possibly of no great advantage to have many steps, but as a rule the more steps there are, the easier is the service on the controlling apparatus, and the more running speeds are available.

With regard to the application of the system to locomotives, on the steam roads where the systems are not tied up with existing electric plants, it is probable that in time the railroads will adopt their own pressures, and possibly their own frequency. This may not be 25 cycles but may be somewhat lower. I believe that the electrification of the steam road may be a controlling factor in the change from direct to alternating current in city service. If the large railroads with their own large power plants adopt alternating current throughout, then the towns lying along the roads will in time probably adopt the same power system, and even the large cities will sooner or later adopt the same system. At the present time the railroads, as far as they have gone, have adopted direct current because the cities through which they pass or enter are using direct current. When the railroads make the big end of the project, however, then the cities will adopt what the railroads are using. When this comes about the direct-current railway systems in the cities will be superseded by the alternating.

Mr. C. V. Drysdale: At this late hour in the discussion, I do not propose to take up your time very much, especially as I am afraid that very few of us over in England have had much experience on this important subject. I should like, in the first place, to take this opportunity of congratulating you on this side of the water on having carried this important problem to such an extremely successful issue as has been recently shown in Ballston and in other places. I think this subject has been worked on in several places, yet to America belongs the honor of having constructed the first line of any considerable length working on the single-phase system. We must still further admire the way in which it has been done when we remember that the result has been achieved by getting over the great difficulties that stood in the way of the series motor, and that in so doing it has been found practicable to use the same motive plants on direct- and alternating-current lines. That, in itself, is an enormous advantage over and above that of being able to use the single-phase alternating current.

It would be impossible for anyone to criticize any of the statements that have been made this morning, because they come from gentlemen who have had such exceedingly minute experience in the special branch of the subject, that their remarks must be taken as gospel, at any rate for the present.

My object in taking part in the discussion is rather to bring the matter back to first principles. This subject has been worked upon in many different ways, and although the laminated series motor, which seems to have been the first to give us results, will probably explain and solve the problem, yet

there are some interesting questions as to whether there are any other ways of fulfilling the problem which may have other advantages. There is one thing that does not seem always to be kept in view in traction matters, in the starting of the cars, and that is the very simple matter that in the starting of the car you do not require power, you require force; if you wish to get anything into motion, what you require in the first instance is purely force, and until the body moves, it does not require power at all. One of the great advantages which the steam-engine has over any electrical system up to the present time, is the fact that when you first turn the steam into the locomotive you get the pressure on the back of the cylinder and get the starting force without taking any power from the steam. If it were not for the other disadvantages of the locomotive, there is no question that that one point would give it a strong pull over anything we have electrical, because if we turn to the ordinary direct-current motor, we find that we have to use half, or with one motor, the whole, of the full-load power merely to secure a starting torque. This has several objections. Not only is this uneconomical and wasteful of power, but it throws a sudden strain on the general plant, and furthermore has to be wasted in resistances, and these resistances sometimes attain a considerable magnitude. With alternating-current motors these matters are worse, as we have in addition low power-factors and consequently difficulties in regulation.

The time is too short to refer to many other systems, but I will mention one, that known as the Ward-Leonard system, which at first sight appears to be an unworkable one. In the Ward-Leonard system, as I understand it, the system is to use a single-phase motor coupled to a direct-current generator which runs direct current on the locomotive or cars. Of course, the indirectness of the method seems to put it at fault, but on the continent that method has been developed with considerable hope of success, in fact with considerable practical success; and it has this great advantage that by the use of this arrangement you can start—get your starting effort—with very small power taken from your station. In the other system—it is too well known for me to describe it here—you have your single-phase motor continuously running, and you can do the whole of the regulation of your speed, etc., by merely regulating the excitation of the generator. The result is that it is possible to get the full starting effort with only something like one-third or one-quarter of the full-load current on the motors. That is so important a matter, especially in view of the huge trains liable to be thrown on the plant in the large schemes which we are hoping to see realized in the future, that I think we should give that method the consideration which it deserves, although it at first sight appears to be roundabout. In addition to that, we have the magnificent system invented by your President, Mr. Arnold, and I hope we shall hear more of that in the future. My only object in rising was to ask that we should hear as much about these systems as possible.

President Arnold: I am pleased to be put down as one of the speakers on this subject, but Messrs. Steinmetz and Lamme have so thoroughly covered the subject, and Dr. Drysdale has so kindly referred to the other systems known to most of you, that it is not necessary for me to say much more, particularly as the time is growing short.

I will correct one statement by Mr. Lamme, which rather puts me on the defensive. I understood him to state that his announcement of the single-phase motor made in September, 1902, was the first announcement of a single-phase system. I beg to state that in the month of June preceding, I read a paper on a single-phase railway, known as the Lansing, St. Johns & St. Louis Railway, which was built at that time and which I have since put in operation. I do not think it is just for the statement to be placed on record just in the manner in which it was made. I think Mr. Lamme meant to say that his paper was the first formal paper on the subject, but my road was built and almost ready to operate at the time that he made his announcement.

Now, without further discussing the question, I am going to call upon a gentleman whose name is known to all of you, and introducing him, I am reminded of an anecdote about a little negro boy who sat on a log chopping away with a hatchet. A man coming along the road asked him how old he was and the boy answered: "If you goes by what mother says, I'se six, but if you goes by de fun I'se had, I'se 'most a hundred." If you judge the man who is to address you by his looks, he is a young man, but if you judge him by his experience he is "most a hundred," and is the father of the commercial electric railway. I have pleasure in presenting Lieut. Frank J. Sprague.

Mr. F. J. Sprague: I feel quite embarrased by this pleasant introduction by our worthy President and the reception which you kindly give me. The subject under discussion is one which I will not enter into at any length to-day, for I see by the hungry and thirsty look on the faces of some of the gentlemen present that one o'clock is near at hand, and that they would probably rather adjourn for luncheon than to listen to any discussions whatever.

The subject on the card is how best to use the alternating current in railway motors. It is largely a technical question. The alternating-current motor is like a somewhat brilliant boy, who being exposed to various diseases has contracted a number of them; he has had a moderate experience in mumps and measles, and a touch of typhoid fever, and the various doctors, many able ones here and elsewhere, have administered, sometimes in homeopathic but oftentimes in allopathic doses, large measures of quinine and other drugs. Whether, as the child grows—and we are all hopeful of that child—and he is subjected to the various climatic conditions of commercial introduction and use, those undercurrents of disease common to all fevers will recur, or whether the child will outlive them and become strong and robust is a matter which must be left to future developments.

There is a larger problem, and I will not take over two minutes to speak of it. It is perhaps a more popular one, but of vital interest to us as engineers who are called upon to advise managers and others as to their financial expenditures, and that is: will electricity be used on trunk lines? Our worthy President, with whom I have the honor to be associated on some important work in that line, is very hopeful, and so am I. But what are the reasons which may dictate the adoption of electricity on trunk lines? Will it be because an economical service cannot be gotten by steam? No. Will it be because there cannot be obtained to-day an efficient service?

Again, no. Will it be because of æsthetic reasons? Distinctly not. If electricity be adopted on any trunk line service it will be because of the hard and fast rule of financial necessity, not because we engineers urge it. It will be because the men who raise the money, run the road and have to provide dividends find that it is the best way to do it, and the reasons which will apply to one road are not necessarily those which will apply to another. It is my belief that some of the largest expenditures, and those most fruitful of return to those who own the steam railroads of the country to-day will be for the purchase and control of competing electric railways which, having in the past acquired franchises of undoubted value which cannot be duplicated, have built up a profitable business which they can hold and which will increase. Many a steam railroad will be better off financially and get bigger returns if it gathers in these franchises and systems, and operates its whole property with proper regard to the needs and capacities of each division than by electrification of its main lines, at least for a long time to come. I know there are one or two gentlemen back of me who feared that I would make some break on the subject, so I will close my remarks. I thank you for your kind attention.

President Arnold: We now desire to hear from a gentleman whose early work is known in many fields, especially in the electric lighting field. His name was carried by one of the leading electrical manufacturing companies for many years and it stands to-day on much of the material that was manufactured in the early days. He is a man who has done much research work, and also considerable experimental work on the repulsion motor, a gentleman whom you all know and whom you recently honored by electing him President of the International Electrical Congress. I have much pleasure in introducing Professor Elihu Thomson.

President Elihu Thomson: It is certainly a pleasure to me to listen to a discussion of this kind in a joint meeting of the Institution of Electrical Engineers of Great Britain, the American Institute of Electrical Engineers, and a Section of the International Electrical Congress. It is gratifying to find that there is so little dissent from the statements which have been made as to the future of alternating-current traction. Many of you will recall, no doubt, that at one time the electrical profession might have been said to have been divided into two camps, the alternating-current camp and the direct-current camp. The gentleman who preceded me was probably at that time more to be found in the direct-current camp than any other. The other gentlemen who have preceded me were to be found in the alternating-current camp. It is a fact, however, and those who have visited the power stations on the circular tour have noticed, that the direct-current men have called in the alternating current to help them out, and combine, therefore, the virtues of the alternating current with the virtues of the direct current.

I was connected in the early days, and am still connected, with an organization which had not many prejudices of one kind or another. We had direct current, we had constant current series arc lights, constant-potential direct-current systems, and when the alternating current came we were ready to take that up without prejudice, and find out what there was in it.

In 1886 we put out our original alternating-current apparatus, and finding that the necessity might perhaps arise for motors on the system, it was at that time I undertook to get a motor for that system, a self-starting alternating-current motor, and the first motor of the repulsion type was made in 1886 and finished in the fall of that year. It was a little affair and was found not to operate very well on the higher frequencies, but by connecting it to a machine, which I was using for electric welding, giving 30 cycles, I found it operated very well and satisfied me as to the general features of the machine. That machine, unfortunately, was sent to an exposition and lost—I could never trace it, and it never came back. The Paris Exposition of 1889 had a couple of examples of machines on a little different basis. One of them, I believe, is in England, at the Royal Institution, and another we have at Lynn. It was a machine which was started as a series alternating-current motor, and as soon as it reached a certain speed the commutator was short-circuited and it became an induction motor. It combined, therefore, the elements of both, but I will admit that the design of such machines in those days was poor. We did not have even the distributed winding; we did not have the arrangements and the proportioning which we have to-day; nevertheless those little motors would give a half-horse power for a moderate-sized motor on 125 cycles, which was the highest frequency used. I merely mention these items as matters of history touching on the discussion. They have nothing to do with the discussion as to the different methods and systems of using alternating current in electric railway motors, but I am a strong believer in the field being open for such work. I believe that not only will the direct-current motor maintain its place, but that certain lines of service which the direct-current motor cannot easily take will undoubtedly be taken by the alternating-current motor for railway service, and the exhibition of a system, which you have been able to see in use, and which adapts itself to the use of both currents, is certainly a very instructive one.

President Arnold: It occurs to me that I may not have put my explanation in regard to Mr. Lamme's statement in just the way it should be put. I think what he meant was that his announcement was the first of a purely single-phase commutator motor system. I think with this correction he will accept my statement. He has not sent me any word, but this additional statement is due him. I think my work was first, but he got in with his announcement in September regarding the single-phase commutator motor.

ALTERNATING *vs.* DIRECT-CURRENT TRACTION.*

BY PROF. DR. F. NIETHAMMER.

Even if one considers only serious proposals, there will be found available quite a considerable number of electric railway systems which might be used. None of the known systems possess, however, advantages or features of such a kind as to render it able to replace all others. This fact becomes specially conspicuous, if an electric railway is desired which is adapted equally well to all the various services occurring in railway practice, viz., short and long lines, high and low speeds, short and long distances between stations, heavy and light traffic.

At the present time the following electric systems may be considered:

1. Direct-Current Railways.

a. *Two-wire systems.*— Constant pressure from 500 to 1000 volts on the train, the return circuit being the rails. Motors with large inputs and moderate speeds may, however, safely be built for pressures up to 2000 volts, by using double commutators if necessary, or by grouping several motors in series.

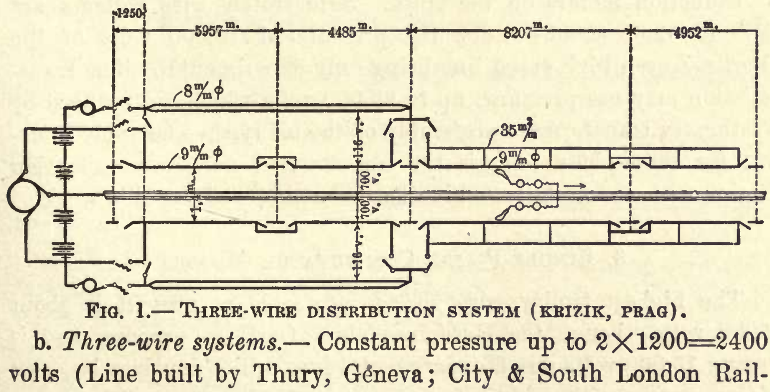


Fig. 1.— Three-wire distribution system (Krizik, Prag).

b. *Three-wire systems.*— Constant pressure up to 2×1200=2400 volts (Line built by Thury, Géneva; City & South London Rail-

* As I did not think it advisable to change the paper as it originally ran, I add an appendix containing the most recent progress. The author treats the above subject in a much more complete way in a German book " Die elektrischen Bahnsysteme der Gegenwart." As to single-phase railway motors see also *Electrical Magazine*, October and November, 1904.

way with 4×500 volts). 2×2000 volts seem to be a safe limit for this system. Each train may either be fed by one branch of the three-wire net-work, in which case the pressure per train is half of the whole voltage, and only *one* trolley is necessary; or each train may take the whole voltage by two trolleys the connection of two motor groups being grounded and the rails being the neutral conductor. (Fig. 1.)

By installing boosters or direct-current transformers in the central station or along the line, the distance which may be covered by the simple direct-current system may be somewhat enlarged; the same result may be arrived at by using storage batteries at some feeding points of the line.

c. *Direct-current railways with transmission by three-phase currents.*— The direct-current pressures on the trains remain the same as under (*a*) and (*b*); the three-phase voltages go as high as 60,000, transformation being by rotaries or motor generators. The transmission may also be effected by the direct-current system with constant current and variable voltage up to 30,000 volts (Thury).

In all the cases mentioned, the simple series motor is almost exclusively used, with the exception of mountain railways with low constant speed. For the latter case the shunt motor is preferable, as this type is able to return energy to the line.

2. Three-phase Railways.

Induction motors on the train. Safe trolley wire voltages are 500 to 3000 (5000) volts, the pressure of 10,000 volts of the Berlin-Zossen high speed line being only experimental. The transmission may use pressures up to 60,000 volts which are reduced by stationary transformers preferably of the oil type.— Of some interest for three-phase lines is the compensated polyphase induction motor with commutator, which has been proposed for this work.

3. Single-Phase Commutator Motors.

The highest trolley wire voltage advisable at present is about 6000 volts, though the Maschinenfabrik Oerlikon proposes and is using 15,000 volts on an experimental line, which involves less risk for a system with one trolley wire than for a system with two or three. There are available for traction three types of single-phase motors: The series motor (Westinghouse Company, General Electric Company), the repulsion motor (Brown, Boveri & Cie)

and the compensated or series-repulsion type (Winter-Eichberg, Union E. G.).

The following systems are of sufficient practical interest to be mentioned, but they cannot be considered serious competitors to the foregoing.

4. Current Changers.

Converters or electric generators *on the train.*

a. *Ward-Leonard system* and shunting locomotive of the Maschinenfabrik Oerlikon. The train takes single-phase current at high voltage from the trolley line and transforms it into direct current by a high-speed motor-generator set. By changing the small exciting current of the direct-current generator, speed control of the train may be accomplished, and during retardation energy may be returned to the line. The main drawback of this excellent system is the excessive weight and price of the motor generator, which weighs more than all car motors together.

b. *Combination of steam engines, steam turbines or oil (petroleum) engines with direct-connected direct-current generators.*—Regulating is done as in case *a.* Of this type is the old Heilmann locomotive and a new car of the North Eastern Railway in England, which latter contains a horizontal oil engine directly connected to a compound generator of 55 kilowatts 300 to 550 volts and 420 to 480 revolutions per minute.

5. Single-phase Induction Motors.

First proposed by C. E. L. Brown but having little chances of being applied practically.

a. Stator and rotor both revolve; the stator is brought up to speed without load. By gradually retarding the stator by means of a brake, the rotor which is connected to the car wheels is put in motion.

b. The induction motor is started empty and connected to the car wheel through a flexible friction clutch.

c. Stator and rotor are connected with a device capable of storing up energy, which device absorbs or delivers energy at will, i. e., an air compressor (B. J. Arnold) or oil pumps with variable stroke (Swinburne) or water pumps (Siemens & Halske). This system possesses the advantage of ability to operate for short distances without connection to the electric supply circuits.

6. Constant Direct-Current System.

Various trains are switched in series by a double trolley wire system. The total voltage is variable, and it is proposed to go as high as 30,000 volts. The constant-current system is, however, too complicated and unreliable for distributing purposes, though it is excellent for transmission lines. Speed variation and starting would be very economical and returning energy to the line very simple. The continuous losses in the line would, however, be considerable.

7. Motor Cars with Storage Batteries.

Independent of every outside source of current and always ready for service. Such locomotives are heavy[1] and expensive and serve only for factory or shunting purposes or for short lines with light and constant traffic and with low acceleration. The mixed service using partly storage batteries and partly overhead line has entirely failed. There were also proposed railway plants combining storage batteries with single-phase induction motors. Starting is done by the battery, free running and charging by the transformed single-phase current.

The above-mentioned systems should be compared with regard to first cost, operating expenses, reliability and safety in service. This comparison is to be made for lines of few kilometers in length (street railways) and for hundreds and thousands of kilometers (main lines), for speeds of 10 km per hour up to 100 and 150 km; for accelerations of 0.1 *m* per sec.^{2} to more than 1 *m* per sec.^{2}, the retardation being even higher by 20 to 40 per cent. The train weights vary from 5 tons to about 2000, and the number of horse-power per train from 10 to 4000. There are lines with only 10 trains a day, on others the trains follow at intervals of 3 minutes. In one case the stations are separated by a distance of only 200 meters, on others more than 100 km. In the first case the whole service is starting, coasting and braking; in the other case free running is of most importance. Either motor cars with multiple unit control for motors distributed over the whole train or locomotives may be used. Electric traction is specially qualified for motor car service of passenger as well as of freight trains which service requires frequent short trains of variable length. Electric

1. A storage battery locomotive for a whole train weight of 100 tons for 16 km an hour weighs 26.8 tons; the storage battery absorbs 10 tons and the remaining electric equipment 4.3 tons.

motors are also able to haul heavier trains than steam engines and to exceed the latter in speed. (Baltimore-Ohio 1600 tons trains. New York Central trains of 2×2200 horse-power, max. 2×2800 horse-power.) Single motor cars take more watts per ton-km than long trains. A very hard problem is offered by motor cars which must be used for short and long distances between stations, for low and high speeds, and for short and long lines and for light and heavy service at the same time. For this service, however, electricy is better adapted than steam.

The main data for usual railway traffic may be taken from the following table, which gives the limiting values corresponding to light and heavy traffic:

TABLE. I.

TRACTION DATA.

Kind of railway.	Max. speed km per hour.	Motors. Number.	Motors. HP. per motor.	Motors. HP total.	Number of cars with motors.	Number of cars without motors.	Weight of train, tons.	Acceleration m. (p. sec.)[2]	Distance of stations in km.
Street railways, with radial lengths of 1 to 30 km from center and gauges of 600 to 1,436 mm..	10 to 30	1 to 2	10 to 60	10 to 100	1	0 to 3	5 to 25	0.1 to 0.3	0.1 to 0.3
Industrial and mine locomotives, gauge 300 to 1,436 mm..........	8 to 20	1 to 4	5 to 50	10 to 200	1	....	20 to 500	small	....
Elevated and underground, 10 to 40 km length, multiple unit.....	30 to 90	2 to 8	30 to 250	60 to 1,500	2 to 3	1 to 5	60 to 250	0.4 to 1.0	0.2 to 2
Suburban and interurban service, 10 to 200 km radial length, multiple unit..................	30 to 120	2 to 8	30 to 200	60 to 1,500	1 to 3	1 to 5	30 to 300	0.2 to 0.7	2 to 15
Main lines locomotives { freight trains....	10 to 40	2 to 8	50 to 500	100 to 3,000	1 to 2	many	50 to 2,000 (mostly 150 to 500)	0.05 to 0.2	2 to 50
locomotives { passenger trains.	20 to 70	2 and more	40 to 400	80 to 1,500	1 and more	many	40 to 500 (mostly 60 to 200)	0.1 to 0.3	2 to 20
locomotives { express trains...	70 to 150	2 and more	100 to 500	300 to 3,000	1 and more	3 and more	100 to 500 (mostly 150 to 250)	0.2 to 0.5	10 to 300
(Steep) Gothard line, 26% grade freight .... passenger..................... express	20 30 40	4 4 4	145 175 200	580 700 800	1 1 1	many " "	350 280 260	very small " "	3 to 20 3 to 10 5 to 20
Mountain Ry	5 to 10	1 to 2	50 to 150	50 to 300	1	1 to 2	10 to 30	very small	1 to 5

TABLE I — TRACTION DATA (*Concluded*).

Kind of railway.	Max. speed km per hour.	Motors. Number.	Motors. HP per motor.	Motors. HP total.	Number of cars with motors.	Number of cars without motors.	Weight of train, tons.	Acceleration m. (p. sec.)[2]	Distance of stations in km.
Example Berlin elevated (direct current)	50	2×3	60	360	2	1	70	0.7	0.3 to 2
New York subway............	about 50	2×3	200	1,200	3	2	about 160	0.7	0.5 to 2
(direct current)............	" 90	2×5	200	2,000	5	3	" 260	....	....
Milan-Portocerisio (direct current)	90	4	150	600	1	1	80	0.35	2 to 10
Valtellina (three-phase).........	....	(concat.)	....	....	....	....	75	0.16	2 to 10
passenger........................	64	4	150	300	1	many	....	....	....
freight	32	4	150	600	....	....	300 (10% grade)	....	....
new locomotive..............	64	2	600	1,200	1	many	250	0.16	2 to 10
	32	2	450	900	....	....	400	....	....
	(concat.)	....	....	....	....	....	....	....	....
Burgdorf-Thun (three-phase)									
passengers........................	36	4	60	240	1	1	55	0.25	1 to 4
freight	18	2	150	300	1	many	130 (25% grade.)	0.1	....
Direct current Baltimore and Ohio locomotives	16	2×4	225	2×900	1	many	1,600 (10% grade)	....	....
New York Central.............	110	4	550	2,200 or 4,400	1	"	550	about 0.7	....

The energy input, the watts per ton-km grow with increasing speed, i. e., an increase from 32 to 128 km per hour means an increase of input of 45 per cent per ton-km. High acceleration certainly requires lowest total watt consumption for starting, but it causes excessively high starting currents, necessitating large and expensive motors and drawing excessive loads from the central station. For short distances between stations it is most economical to run very fast up to a high speed, if admissible, and to coast as long as possible without current. The maximum acceleration depends upon the allowable shock to passengers when starting; much more than 1 m (per sec.)^2 will not be permissible. The best method is to increase acceleration gradually when starting and to let it die out finally without any shock.

Undoubtedly a reasonable electric railway service can be offered in economical competition with steam. On the Italian line from Milan to Porto Cerisio (130 km direct length, 70-ton trains, acceleration 0.35 m (per sec.)^2 and speed of 90 km), the introduction of electric service has increased the number of travellers 2½ times, the train-km 4 times and the trains per day have grown to 120 from about 20 during steam service. The receipts and profits obtained render this line the most economical in all Italy, though steam is used for generating electricity. Most favorable to electric traction are most urban and suburban lines, railways with dense traffic or those so located that the traffic could not be increased without an additional line, railway tracks with long tunnels and heavy grades and lines which are in the neighborhood of coal mines and water powers.

A comparison of the various electric systems should comprise the whole electric equipment, viz.: *a.* Motors and gearing; *b.* regulating and braking devices; *c.* current-collecting devices; *d.* central stations and sub-station equipments.

Motors.

The characteristic features of railway motors are,

1. Mechanical reliability.
2. Maximum pressure possible on motor terminals and maximum pressure at the trolley.
3. Sparking on commutator or collector.
4. Weight per horse-power at a definite speed.
5. Space occupied by motor.

With heavy train loads, high speeds and great accelerations it is often extremely difficult to make sufficient space available on the car truck for the large motors required. The room available increases with increasing diameter of the wheels and with broader gauges. It is a fact, that on a 300-mm gauge only 15-hp motors are possible, on a 700-mm gauge only 90 horse-power, on 1000-mm gauge about 150 horse-power and on normal gauge 250 horse-power.

6. Efficiency at full and partial loads.

7. Starting losses of the motor.

8. Power factor at full load, partial loads and at starting.

9. Heating for normal continuous running and for frequent starting.

10. Starting torque and possibility of producing high acceleration; current consumption for a definite starting torque.

11. Efficiency of acceleration.

12. Speed variation; losses and efficiencies at variable speeds. Steadiness of regulation. Speed characteristic for variable loads.

13. Braking on resistances and return of power into the line, when coasting or on grades.

The direct-current series motor has an air-gap of 2.5 to 7 mm for usual armature diameters of 300 to 600 mm, the upper gap being smaller by ½ to 1 mm than the lower. Experience on hundreds of thousands of such motors prove that this air-gap is absolutely safe and that there is no danger of sticking. The direct-current armature winding, with open slots and carefully wound separate coils, as well as the commutator, may be insulated in an absolutely reliable way for voltages up to 2000. The field winding has no high potential between its terminals and is easily protected against the frame, whilst the field winding of shunt motors, being subject to full pressure, is much more liable to break down.

The induction motor, if only that type without commutator is considered, must have an air-gap from 1 to 3 mm in depth for usual railway motors, according to size, in order to secure a satisfactory power factor and a sufficient overload capacity. The Valtellina motors with a rotor diameter of 800 mm have an air-gap of 2 mm. Values for other machines may be taken from Table II. According to the long practical experiences of Brown, Boveri & Cie., and of Ganz & Company, this small air-gap has never given rise to trouble, when the bearings are liberally designed. C. E. L. Brown has successfully used automatic ring lubrification for three-phase motors. Nearly closed slots should preferably be used to get smooth cylin-

drical surfaces along the air-gap, which makes it a necessity to wind the coils by hand. This type of winding with closed mica tubes in the slots and end connections well protected by bronze caps has never caused trouble on the Burgdorf-Thun or the Valtellina line. Special care must be given to the crossings of the end connections, but insulation may be obtained to withstand easily pressures up to 5000 volts. High voltage motors must, however, be very liberally dimensioned to keep down heating which deteriorates insulation. It may be of advantage to put the stators of two three-phase motors in series to reduce the voltage per motor (Fig. 2).

The air-gap of the single-phase commutator motor must also be rather small, though larger than with the three-phase motor, i. e., 3 mm for a rotor diameter of 450 mm. Commutator motors, the rotors of which are not fed directly from the line, are the best machines for high voltages up to 8000 volts, as all crossings of the end-connections can be easily avoided. For equal line voltage

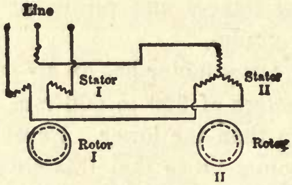


FIG. 2.—STATORS IN SERIES.

the single-phase motor in comparison with the direct-current motor is at a disadvantage in that there is an active e.m.f. across not only the armature but also the field coils.

The trolley voltage of all alternating current equipments of the single or polyphase type may be lowered at will by transformers on the car, if on account of limited space or due to troubles on the commutator, one is bound to use low voltage motors. That means, however, additional weight and expense, though the transformers may be used for regulating purposes at the same time.

The frame of single or polyphase motors can hardly be split, as is frequently done with direct-current machines. The joints might give rise to noise. As, however, even for direct-current motors in limited space the splitting of the frame is being abandoned in favor of the box frame, this fact is not of much importance. From Fig. 3 which represents a single-phase commutator motor of the Union Company, Berlin, for 50 horse-power, 800 rev. p. min., 40

periods, 6 poles, 400 volts, it may, however, be seen that the splitting of an alternating current motor is not an entire impossibility. Single-phase winding is more favorable yet, as no coils have to be cut. The laminated field of alternating-current motors is less rigid than that of the direct-current machine, so that an additional solid frame becomes necessary. For direct-current motors which must undergo rapid variations of the magnetic flux and of the speed or which must be quickly braked, a laminated frame would, however, also be of advantage.

The greatest drawback of direct-current motors is the difficulty of commutation. Sparking in the neutral zone is due to the reactance voltage of the short-circuited coils and to the voltage induced by the distorted main field. The distortion may be kept low by using a high number of field ampere turns and high saturations of

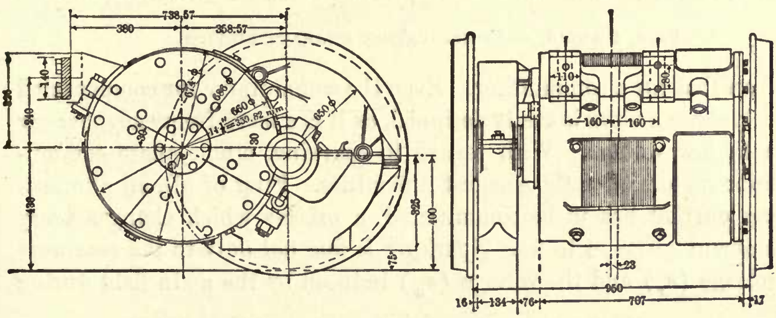
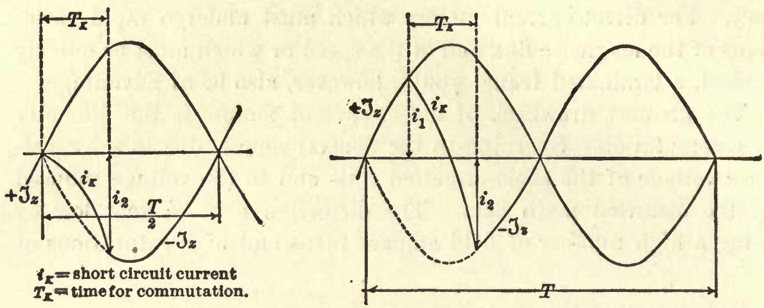


FIG. 3.—50-HP SINGLE-PHASE MOTOR, UNION COMPANY.

teeth and pole shoes. The reactance is small for low speed motors, for short armatures, for small currents per armature circuit, and for commutators with many segments. Flashover is produced by high voltages per segment and by current rushes, when at high speeds the current circuit is suddenly opened and closed again. These are the reasons why direct-current motors have not been built as yet for more than 1000 volts, though larger low-speed types may successfully be designed for about 2000 volts. To raise the trolley voltage, several motors may be switched in series, but this scheme has the drawback that when some wheels with motors are slipping and others not, one or several motors may get the full voltage at their terminals and be burned out. The series motor is, of course, much less liable to sparking than the shunt motor, as the reactance does not vary much with load and speed, besides that armature and field ampere-

turns increase together. This commutation trouble is the most serious handicap to the direct-current motor, as it limits the extension of its supply lines.

The three-phase motor has no commutation problems. The space for the three slip rings with carbon brushes is, however, not smaller



FIGS. 4 AND 5. — COMMUTATION CHARACTERISTICS.

than that for a commutator. Even the commutator for compensated polyphase motors is easily designed, as it is a mere frequency changer with low voltage. With regard to sparking, single-phase commutator motors offer the greatest difficulties. First of all, an alternating current has to be commutated, a process which changes every moment (Figs. 4 to 6). Sparking is due not only to the reactance voltage (e_r) and the voltage (e_a) induced by the main field during

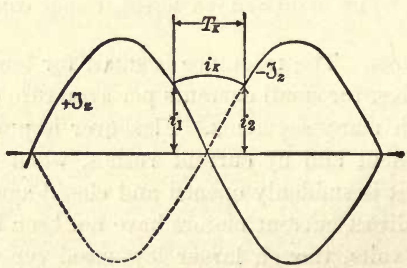


FIG. 6 — COMMUTATION CHARACTERISTICS.

rotation, but to a transformer voltage e_t which is induced by the oscillations of the main field independent of speed and which produces a high short-circuit energy. By using low commutator voltages (smaller than 200 volts). a high number of commutator bars preferably with multiple parallel winding, by selecting thin brushes

(minimum 6 to 10 mm), by inserting high resistances into the short-circuited coils, by reducing the main field and by building only motors for small outputs and small periodicities, the transformer voltage, e_1, may be kept sufficiently low. The reactance voltage, e_t is cut down by the same expedients as used for direct-current motors. Equalizers and auxiliary commutation poles may be of advantage, but there will rarely be space available for them. By a double (horseshoe) pole excited by the main current opposite to the short-circuited coil, one may neutralize the whole transformer effect. The General Electric Company uses a distributed field winding to neutralize the reactance voltage similar to the Ryan winding of direct current machinery.

The repulsion motor and the compensated motor (Fig. 7) have this advantage that for synchronism, and in its neighborhood, a regular rotating field is built up, replacing the pulsating alternating fields. Near synchronism the transformer effect in the coils under

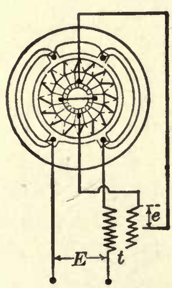


FIG. 7.—COMPENSATED MOTOR.

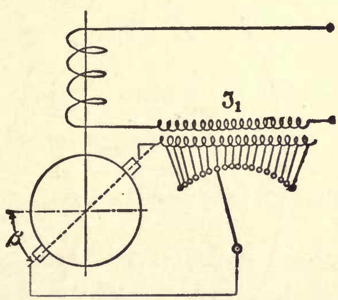


FIG. 8.—STARTING COMMUTATOR MOTOR.

the brush is, therefore, eliminated and the commutation is similar to that of direct-current machine. Flashing over on the brushes of a repulsion motor seems next to impossible and even for other commutator motors flashover appears less probable, as self-induction damps away sudden current rushes and the laminated stator frame facilitates the rapid building up of magnetic fields.

When starting, all commutator motors are equally bad and one of the best schemes besides those already mentioned is to use a series transformer for the armature circuit (Fig. 8) which cuts down the starting field, allowing at the same time any intensity of the starting current. For repulsion motors, the same effect is possible by shifting the brushes toward the position of complete transformer action (brush axis in line with field axis). The main

field at starting may also be prevented from rising too much by choosing the iron inductions very high.

The distortion of the field by armature reaction and the wattless voltage component produced by it may easily be neutralized for the single-phase series motor by a field winding, the axis of which coincides with the armature cross-field and which may be short-circuited or in series with the armature current circuit. Figs. 9 and 10 show this arrangement as used by Ganz & Company 15 years ago. Finzi splits the poles for the same purpose and cuts down the polar arc. Blathy of Ganz & Company also used some 15 years ago high tooth inductions[2] and ohmic and inductive resistances between armature winding and commutator, sometimes imbedded in the slots.

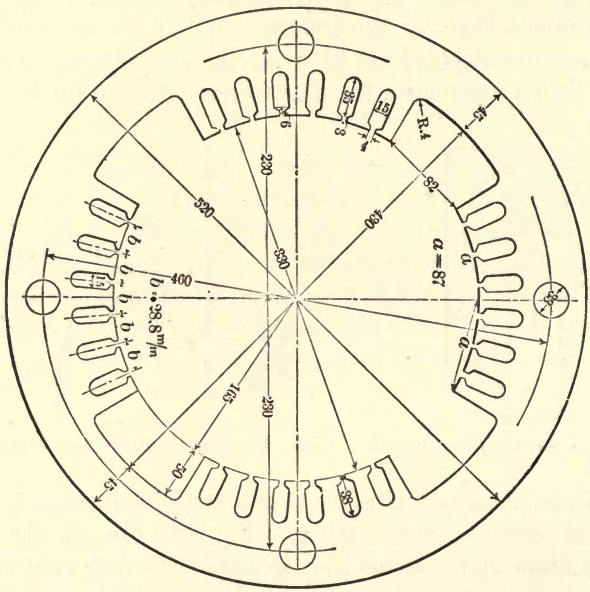


FIG. 9.— STATOR PUNCHING.

A stator with definite projecting poles has the advantage of cutting down the reactance voltage in the short-circuited armature coils and gives rise to smaller armature cross-field, which means a better power factor than with a distributed winding imbedded in slots equally spread round the whole circumference. This is the reason why series motors should always have definite poles, while

2. Lamme proposes high pole-shoe induction.

the good operation of repulsion motors depends upon the full development of the armature cross-field to get a rotating field at synchronism. Repulsion motors must, therefore, have a distributed winding. The better leakage factor of the last-mentioned winding

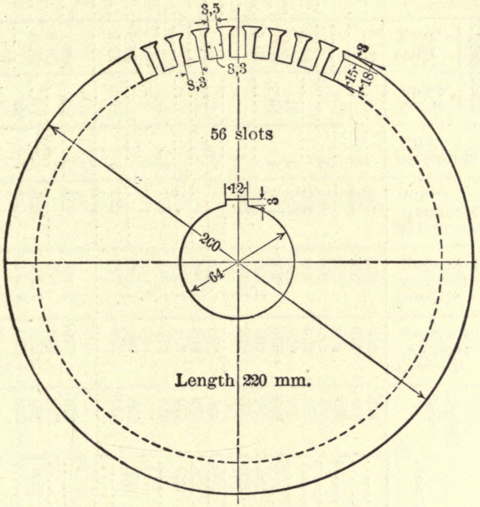


FIG. 10.— ROTOR PUNCHING.

is outbalanced by the better voltage factor or winding efficiency of a concentrated winding.

Table II shows weight, outside dimensions, air-gap, efficiency, etc., of a great many railway motors of the direct-current, three-phase and single-phase type, most of which are in actual service:

TABLE II.

DATA OF RAILWAY MOTORS.

a. *Direct Current.*

Number	Manufacturer.	HP.	Rev. p. min.	Volts.	Gear ratio.	Gauge in mm.	Weight in kg. Total.	Weight in kg. Without gear.	Weight in kg. Armat.	Height mm.	Breadth without gear mm.	Length without gear mm.	Armature diameter mm.	Air-gap in mm.	Efficiency. Motor alone.	Efficiency. With gear.	Power factor.
1	G. E. Co., N. Y.	21	450	500	1:4.8	1,000	780	630		540	540	590	280			78.2	
2	Oerlikon	24								600	650	700	335	2.5			
3	Brown, Boveri	25	300	550	1:5	1,000	1,000			700	550	800			85		
4	Ganz & Co.	25	560	500	1:4.87	1,200	1,000			615	670	960	406	3			
5	G. E. Co.	27	700	500	1:4.8	600	700			580	510	430	350			81.6	
6	Alioth	31	600	500	1:4.2	1,000	770			620	660	770	330	3	84	81	
7	"	38	480	350	1:4.1	1,000	890			640	670	770	380	4	86	80	
8	G. E. Co.	38	520	500		normal	1,070	950	250	640	680	1,000	370			83.5	
9	Siemens-Halske	39	430	500	1:4.8	normal	1,560	1,400	308	670	670	1,100	340				
10	Ganz & Co.	45	750	500	1:3	normal	1,750			740		1,100					
11	A. E. G.	50	500	500	1:3.2	1,250	1,233	1,075		625	740	990					
12	Schuckert	54	600			normal	1,780	1,530		620	650	1,100					
13	Westinghouse	55	475	500	1:3.5	normal	1,360	1,220	330	610	610	1,160					
14	Siemens-Halske (Elevated Berlin)	52	800	750	1:4.1	normal	1,580	1,400		660	660	1,070	342	3.5	85		
15	G. E. Co.	65	540	500	1:4.5	normal	1,600	1,400	350	700	740	1,100				86.5	
16	Alioth	65	450	750	1:4.8	1,000	1,350			640	730	770	420	5	84.5	87.5	
17	Siemens-Halske (Wannsee)	70	260	600	no gear	normal	1,100	3,000									
18	Westinghouse	75	500	500	1:2.8	normal	2,000	1,800		700	720	1,150	400		84	88	
19	Eborall	80	710	500		normal	1,530			720	950	830		6.4		88.5	
20	G. E. Co.	80	500	500	1:4.8	normal	1,800	1,600	500	740	710	1,100	450	4.4		88.5	
21	Brown, Boveri (Open)	85	700	275	1:13.6	1,000		2,000		950	1,000	1,300	450	7	92		Open shunt motor (Mountain Ry.)
22	Rieter	90	450	375	1:4.1	1,000	1,700			750	700	730	440	4.5	85	89	
23	Oerlikon	100	550	900		1,000	1,700		440	685	740	780	415	2.5			
24	Siemens-Halske	100	370	600	1:4.5	normal	2,250	2,000	550								
25	Westinghouse	100	435	500	1:2.4	normal	2,400	2,270	610	750	750	1,250					
25a	Oester-Union	100	700	600	1:12.2	normal		1,900		990	1,050	1,300	500	2.5		93	Open shunt motor (Mountain Ry.)
26	Dick, Kerr	110	570	500	1:2.9	normal	1,820	1,640									
27	G. E. Co.	125	540	650	1:4.9	normal	1,990	1,790	600	740	730	1,100	460	3.95		89	

TABLE II — (*Continued*).

Number.	Manufacturer.	HP.	Rev. p. min.	Volts.	Gear ratio.	Gauge in mm.	Weight in kg. Total.	Weight in kg. Without gear.	Weight in kg. Armat.	Height mm.	Breadth without gear mm.	Length without gear mm.	Armature diameter mm.	Air-gap in mm.	Efficiency. Motor alone.	Efficiency. With gear.	Power factor.
28	Thury (Open)	125	400	4×600	1:4	normal	8,050	...	...	900	1,150	1,500	750	...	92	...	Six poles
28a	Siemens	50	330	600	1:1	normal	...	2,500	...	...	...	...	520	5	83	...	...
28b	Siemens	80	360	500	1:6.3	1,000	...	4,000	...	...	...	...	500	6	85	...	Mountain Ry.
28c	Siemens	140	430	530	1:9.2	1,000	...	4,800	...	...	...	...	500	7.5	86	...	" "
29	Schuckert	130	330	500	1:1	normal	4,750	...	...	...	...	...	...	...	...	...	...
30	Westinghouse	150	550	500	1:2.9	normal	2,400	2,250	670	735	830	1,260	...	...	...	...	...
31	Oerlikon	150	450	750	1:4	normal	3,050	2,700	840	900	1,000	1,070	550	4	...	84.5	...
32	Siemens-Halske	155	610	750	1:4.5	normal	2,900	2,670	700	...	...	...	...	...	...	...	...
33	Dick, Kerr	150	470	500	...	normal	2,800	...	...	920	850	1,070	420	...	...	...	...
34	G. E. Co.	165	570	500	1:2.5	normal	2,400	2,200	700	740	660	1,000	450	...	...	87	...
35	G. E. Co. (N. Y. Subway)	200	500	600	...	normal	2,800	...	...	740	790	1,080	...	5.5	...	90.5	...
36	Westinghouse (Subway)	200	500	600	...	normal	3,000	...	870	740	...	1,150	500	...	...	...	...
37	G. E. Co. (Central London)	200	190	500	no gear	normal	5,400	...	1,850	820	1,160	1,340	570	7	91.3	...	...
38	Siemens-Halske	210	520	750	1:4.7	1,000	6,100	4,800	1,000	...	...	...	500	...	...	...	...
39	Oerlikon	220	645	500	...	normal	3,000	2,600	760	...	...	...	...	...	...	...	...
40	G. E. Co.	250	360	500	1:4.1	normal	3,700	3,600	1,100	960	760	1,060	600	7	...	87	...
40a	G. E. Co.	550	300	600	1:1	normal	...	...	...	...	...	...	760	...	92	...	...
	b. *Three-phase.*																
41	Brown, Boveri	35	400	500	1:3.8	1,000	...	830	...	900	700	700	450	1.25	85	...	0.75 for 40 periods.
42	" "	35	480	750	1:3.6	1,000	...	960	...	900	700	750	410	1.25	87	...	0.80 for 32 "
43	" "	60	600	750	1:3	normal	...	1,500	...	1,000	780	1,000	500	1.5	88	84	0.85 for 40 "
44	" "	75	650	750	1:16	1,000	...	2,000	...	1,020	1,045	1,255	640	1.5	91	...	0.88 for 32 "
45	Eborall	80	717	500	...	normal	1,700	...	...	1,020	1,020	1,030	440	1.8	...	90	0.835 for 50 "
46	Brown, Boveri	90	800	500	1:12	1,000	...	2,050	...	860	1,040	1,030	640	1.5	91	...	0.88 for 40 "
47	Oerlikon (Open)	120	750	500	1:12.6	1,000	...	2,100	+300 for exciter	1,050	1,050	1,050	600	1.2	92	...	0.90 for 40 "
48	Brown, Boveri	150	760	500	1:11.6	1,000	...	2,700	...	1,180	1,040	1,050	640	1.5	91	...	0.90 for 40 "
49	" "	150	300	750	1:1.88	normal	...	4,000	...	1,700	1,860	1,050	1,200	3	92	...	0.85 for 40 "
50	Siemens-Halske	200	900	10,000	1:2	normal	...	4,100	...	1,150	1,150	1,100	680	1.5	90	...	0.90 for 50 "
51	Ganz & Co.	250	300	3,000	no gear	normal	...	3,800	...	1,160	1,160	1,300	800	2	93	...	93 for 15 "
52	Siemens-Halske	250	900	1,000	no gear	normal	...	4,000	...	1,040	1,040	1,300	720	2.5	92	...	94 for 50 "

TABLE II — (*Continued*).

b. *Three-phase* — (*Continued*).

53	A. E. G	250	960	435	no gear	normal	cooled	3,200	....	960	960	1,160	584	......	......	......	94 for 50 "
54	Ganz & Co.......	500	225	3,000	no gear	normal	....	6,500	....	....	....	....	....	......	93	......	93 for 15 "
55	{ "	600	225	3,000	cranks	normal	....	12,400	....	1,725	1,775	1,300	1,400	2	......	......	93 for 15 "
	{ Double motors.	450	112	....	1:1	....	....	....	....	....	....	....	....	......	......	......	....

c. *Single-phase commutator motors.*

56	Finzi	27	700	750	1:4.8	1,000	800	....	....	....	....	....	....	......	......	76	90 for 18 periods (straight series)
56b	Oerlikon.........	35	1,000	250	....	....	1,000	....	....	....	....	....	....	1	82	......	....
56a	Union E. G.......	50	800	400	1:5.07	1,000	1,240	....	....	690	690	820	....	......	......	75	ca 95 for 40 periods.
57	Union E. G.......	120	700	6,000	1:4	normal	2,360	2,700	....	750	920	1,052	ca 450	3	87	83	ca 95 for 25 periods. (Winter Eichberg)
57a	Westinghouse ...	150	200	200	....	normal	....	2,500	....	....	....	....	....	......	......	......	....
58	Oerlikon.........	145	300	200 (15,000)	....	normal	....	3,000	....	....	....	....	....	......	......	......	15 periods (straight series motors).
59	Oerlikon.........	200	450	200 (15,000)	....	normal	....	3,400	....	....	....	....	....	......	......	......	15 periods (straight series motors).
60	Oerlikon.........	200	650	400	1:3.1	normal	....	3,000	....	1,250	1,250	1,150	750	......	92	......	15 periods (series motor), 96%.

For equal output, speed and voltage the direct-current motor has usually the smallest weight, is cheaper and takes less space than all its rivals. The reasons are: That the field is solid and there are no lagging currents, the concentrated field winding is very simple and it needs no inactive frame, the inductions in all iron parts may be very high, in the teeth up to 27,000 lines per cm^2, in the core 15,000 to 20,000, in pole and yoke the same,[3] whilst alternating-current motors cannot at all reach these values on account of the high wattless magnetizing current. Three-phase motors with variable poles or concatenated motors have even higher weights. The commutator of single-phase motors must be larger than that for direct-current machines on account of the much higher commutator losses and because the voltage must be kept very low (less than 200 volts). If both a single-phase and a direct-current motor are laid out for the same maximum field flux Φ_{max} and the same effective current I, the normal torque T_a of the alternating-current motor becomes

$$T_a = \frac{1}{\pi}\int_0^\pi \Phi_{max.} \cdot I \cdot \sqrt{2} \cdot \sin^2 a \, d\, a = 0.71\, \Phi_{max} \cdot I$$

and that of the direct-current type T_d

$$T_d = \Phi_{max} \cdot I$$

That means for the same torque and output the single-phase motor must be 30 per cent larger. For placing a motor into the car truck, a cylindrical body (alternating-current motors) is less practical than a prismatic one (direct-current). As on varying grades and during starting the three-phase motor absorbs more energy than other motors, it must be larger and more expensive for this reason also.

The efficiency of direct-current motors is sometimes somewhat smaller than that of three-phase motors, which result is due exclusively to the much smaller air-gap with the latter machine. For the same air-gap and for open slots, the three-phase motor must have a lower efficiency. Single-phase commutator motors have a poorer efficiency than direct-current and three-phase motors; with partial loads the efficiency is especially very low. The losses of the single-phase motor usually amount to 15–35 per cent more than those of the direct-current type. The increase of losses is due to ad-

3. The current densities are 5 to 7 amps. per mm^2 in the armature and 2 to 3 in the field, in three-phase motor 4 to 5.

ditional iron losses in the field and armature at standstill and when running, and furthermore, to the energy loss in the coils short-circuited by the brushes. For the straight series motor, there may be additional losses in resistances of the commutator connections and in auxiliary windings. The repulsion motor has the advantage that the iron losses in the rotor are zero for synchronous speed.

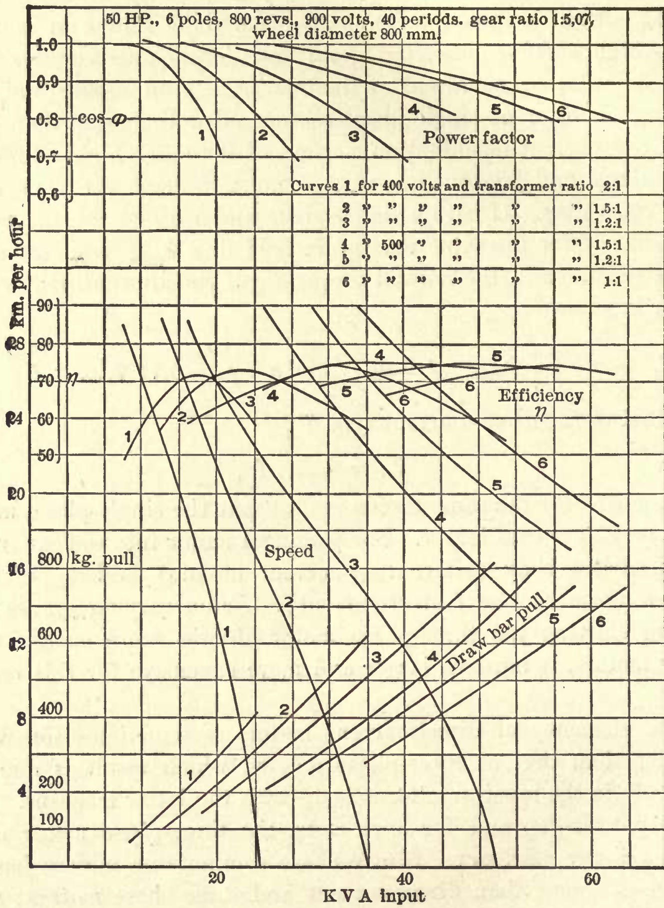


Fig. 11.— Characteristic curves compensated series motor.

Fig. 11 represents all characteristic curves of the compensated single-phase motor the outline of which is given in Fig. 3. Fig. 7 shows the way of connecting up the motor. The curves marked 1 to 5 correspond to a variable ratio of the series transformer.

While with alternating-current motors the number of poles is fixed by the synchronous speed or for the series motor by about double synchronous speed, and by periodicity, which is usually kept low to reduce the number of poles, nearly all direct-current motors have four poles, rarely six. The tendency to building high-voltage motors makes the use of only two poles advisable. This scheme, which is used by the General Electric Company for the 550-horse-power motors of the new locomotives of the New York Central, allows the utilization of the available space in an excellent manner, by laying the pole axis horizontally and leaving all the height for the armature and commutator diameter. The whole length of the car axle is free for the armature as the field and brush yokes are closed outside the wheels. Almost all direct-current motors have six to twelve coils per slot, which means a number of commutator bars equal to three to six times the number of slots, which makes them cheaper and safer than three-phase motors for which a large number of slots is desirable in order to obtain a good power factor.

The *power factor* of three-phase motors is kept high by using high speeds and low periodicities, which render generators and transformers more expensive, but are favorable for the line. For railways with the exception of high speed lines only periodicities lower than 25 are suitable. For given volume and rotor diameter, nearly closed slots produce a better power factor than closed slots. By using a three-phase commutator on the rotor, the phase displacement, which increases the first cost of the whole plant, may be almost entirely compensated.

The *power factor* of single-phase commutator motor equals usually or even excels that of three-phase motors and reaches values of 0.95 or more. But it is necessary or advisable to use frequencies of 25 and less and small air-gaps which may, however, be somewhat larger than with three-phase motors. The ratio field ampere-turns[4] to armature ampere-turns must be small, f. i., 20 to 27; for the repulsion motor this ratio is changed at will by shifting the brushes. For the series motor the normal speed must be equal to one and one-half to two and one-half times the synchronous speed (Westinghouse 1.8 times) and the cross-field must be compensated.

4. The old Ganz motors built 15 years ago had an armature voltage 30 per cent higher than the field voltage, and with them was used a switch to vary the number of field coils; a transformer for the exciting current is also mentioned in the patent.

The series motor which is built with many poles in comparison with the repulsion motor increases continuously its power factor, when the speed surpasses synchronism, whilst the repulsion motor has its maximum near synchronism. For partial loads the power factor of the repulsion motor is better, for normal speed there is no essential difference. By inserting a series transformer in the armature circuit of the compensated motor, one may obtain $\cos \phi = 1$ for various speeds.

Table III gives an interesting comparison of power factor and efficiency for three-phase motors and various methods of regulating them:

TABLE III.

Full speed.	Half speed.				
	Concatenated motors.	Variable number of poles.	Rotor resistance.	Primary compensator.	Variable frequency.
Efficiency 81	—	—	—	59	— } Same motor.
88	—	—	43	—	87 } Same motor.
86	—	74	—	—	—
85	75	80	—	—	—
90	81	86	—	—	—
93	85	89	—	—	—
Power factor 85	60	60	85	75	85
93	77	84	93	85	93

With light loads the power factor of three-phase motors is usually very poor, and the mean value is sometimes as low as 0.5. For starting however the $\cos \phi$ is 0.8 to 0.95. The opposite is the case for single-phase motors, the power factor at starting is extremely low, about 0.3, increasing with speed and decreasing with load.

Of all motors the direct current shows by far the smallest losses in the motor itself when starting with same torque, mainly because the iron losses are zero at standstill and the starting current is least for a given torque. From this fact it results that a direct-current motor heats least, when frequently started.

The following Table IV gives a comparison of the motor losses at starting for various types of motors and starting arrangements.

TABLE IV.

Motor losses for a complete run of a 160-ton train on an elevated railway at a speed of 30 km and a distance between stations of about 1300 metres. Motors 250 to 300 hp.

System*	Direct current.			Three-phase rheostatic control.			Three-phase† star-mesh-connection rheostatic control.			Three-phase concatenated motors.				Single-phase commutator motors series motor.			Single-phase commutator motor compensated type.		
After seconds	0	18	61	0	32	76	0	32	76	0	16	32	76	0	18	61	0	18	61
Iron losses in watts	0	1,000	500	1,300	1,100	1,000	3,500	3,000	1.000	2,500	2,500	1,300	1,000	1,000	2,000	2,000	1,000	1,500	1,300
Copper losses in watts	3,000	3,000	1,000	4,500	4,500	500	1,200	1,200	500	7,000	7,000	2,500	500	4,000	4,000	2,000	3,500	3,500	1,500
Mean total losses in watts	3,500	2,300		5,700	1,500		4,450	1,500		9,500	3,800	1,500		5,500	4,500		4,700	3,500	
Time in seconds	18	43		32	44		32	44		16	16	44		18	43		18	43	
Losses × seconds = watt-seconds	63,000	99,000		183,000	66,000		144,000	66,000		155,000	62,000	66,000		99,000	194,000		85,000	152,000	
	162,000			249,000			210,000			323,000				293,000			237,000		
Ratio of total losses in watt seconds.	1			1.53			1.29			1.98				1.80			1.46		

* A motor with a variable number of poles will give slightly better results than concatenation.
† The stator winding is mesh connected for starting and star connected for free running, which necessitates a rather complicated switching device.
Remark: For case 1, 5 and 6 coasting of 15 records is supposed, for the other cases there is no coasting. **The time for the whole run is the same in all cases.**

Since in the direct-current motor most of the losses are produced far away from the motor surface, the capability for radiating heat is better for the alternate-current motor and best for the three-phase machine. For equal losses the difference in favor of the three-phase motor may amount to 25 per cent. The distributed winding is also better for cooling than the mummified concentrated field coils, for which latter copper strips on edge are best.

In heavy locomotives or motor cars for high acceleration, it may occur that there is not sufficient space for the necessary motor capacity at a predetermined rise of temperature. This limit is much sooner reached by three-phase and single-phase motors than by direct-current motors, and of all motors concatenation is worst in this respect. In extreme cases artificial cooling becomes necessary. The air of the running train may be directed by special pipes and chimneys on the surface of the motors and starters. If it is

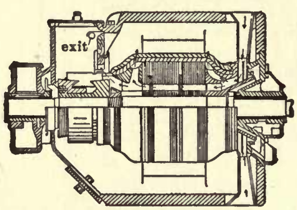


FIG. 12.—G. E. CO. MOTOR.

possible to use openings covered by gauze or perforated sheets at both ends of the motor, one may drive an air draught through the motor by the ventilating ducts of the armature, thereby throwing the heated air to the outer surface. The new G. E. motors for the New York Subway are ventilated similar to Fig. 12 by means of air entering near the back bearing and passing through armature ducts of variable breadth over the field coils and escaping through holes in the yoke. The waste air of the universally used air-brake may also serve for cooling purposes; the pressure of the air must, however, be kept very low to avoid the creeping of oil. If there is sufficient space on the shaft, there may be added a fan to the motor. Reichel proposed to install these fans inside the secondary motors of a concatenated group, and to cool the main motors from these fans.

There are other means for saving space: Siemens & Halske (German patent 131,299) propose to put the commutator outside

the car frame to leave all the space inside available for the armature. In this case, however, the axle must be hollow and many connections through the bearings are necessary. This scheme may, however, be much better realized for the three slip rings of three-phase motors, as may be seen from Fig. 13, which shows the very interesting concatenated motors of Ganz and Company for the new Valtellina locomotives. (Each motor for 600 horse-power, 225 revs. p.

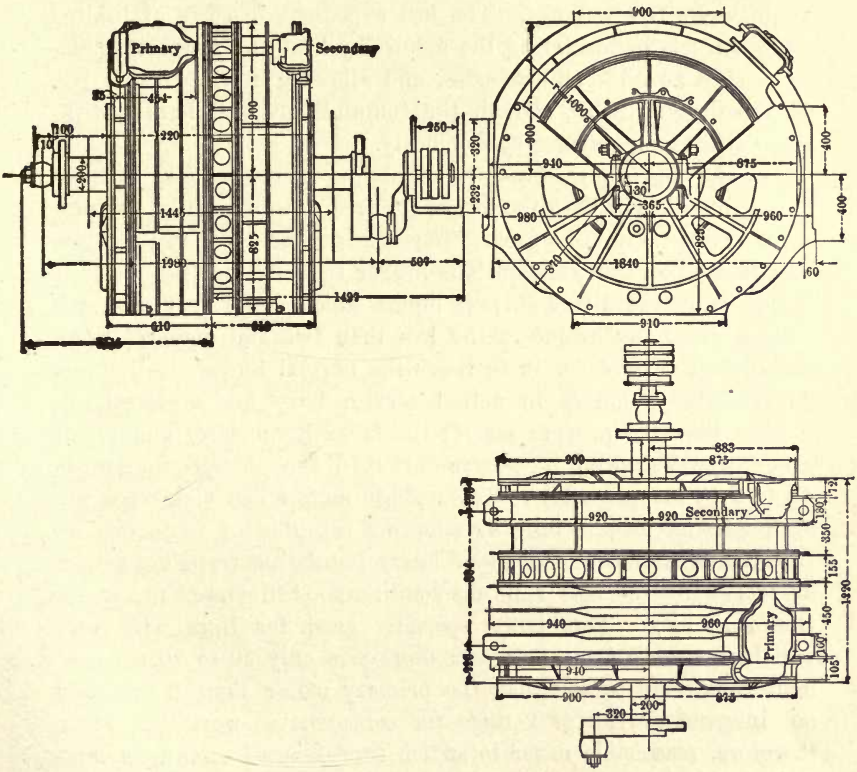


Fig. 13.—Concatenated motor, Valtellina locomotive.

min., concatenated 500 horse-power, 112 revs. p. min., 15 periods, 3000 volts.) To best utilize the given height, the projecting poles of direct current and single-phase motors must be arranged at 45 deg. on an octagonal frame with two sides horizontal; the most favorable design for getting a large armature diameter is to use a bipolar frame putting the poles horizontally and closing the yoke with its bearings outside the frame as is done by the General Elec-

tric Company for the New York Central motors. Kandò cuts off a segment of the cylindrical stator iron of three-phase motor at the lower side. (Fig. 13.) On locomotives there is sometimes sufficient space to put the motors above the car truck, the design being much simplified thereby. There are, in fact, cases where the motors may be of the open type, if they are well protected inside the car box (Jungfrau locomotives). As soon as it becomes possible to build reliable ball bearings, these may be used to reduce the space absorbed by the bearings. The last expedient in cases of limited space consists in insulating the motors by heat and fireproof materials, such as mica and asbestos, and allowing a temperature rise of 100 deg. or more, though the commutators will hardly withstand these temperatures continuously.

The *starting torque* of motors for high accelerations may be three to ten times larger than the torque for free running, whilst for slow speed trains there is no great difference between these two torques. The best motor for accelerations higher than 0.5 m (per sec.)^2 is undoubtedly the direct current motor which starts very economically against any torque taking less than two and one-half times the normal current for three times the normal torque. All three-phase railway motors in actual service have low accelerations, smaller than 0.3 m (per sec.)^2; the large locomotives and motor cars on the Valtellina lines have only 0.16, though tests were made up to 0.45 m (per sec.)^2. Three-phase motors can yield specially high starting torques only by adopting complicated switching devices (mesh-star connection) or heavy regulating transformers, or by sacrificing the best running conditions (bad power factor for free running). This holds specially good for lines with very variable grades. Concatenated motors give only 50 to 70 per cent more maximum torque than the primary motor alone if one does not increase the motor voltage for concatenated working. It is, therefore, reasonable never to switch concatenated motors in multiple, but to leave the secondary motors idle for full speed. Moreover the acceleration up to 50 per cent of synchronism must be double of the value after 50 per cent of synchronism which is also true for the mesh-star connection.

The starting torque of the single-phase motor is for a given voltage the highest possible torque just as for the direct-current motor. On account of sparking difficulties and self-induction, the maximum torque is, however, smaller, but may be three to five

times the normal torque for well-designed types. The starting current is nearly entirely wattless, but is only about two to two and one-half times normal current for three times the normal torque. When starting very slowly with a large torque by a strong field, the short-circuit effect under the brushes may burn out the motor. The torque of a single-phase motor, which is 30 per cent smaller than that of a corresponding direct-current motor is not constant as is true with direct and three-phase current machines, but varies between a maximum and zero with double the periodicity of the line current. The mean value of the torque is only half of the maximum, which fact is very important for the limit of slipping of the wheels. The wheels slip when the mean useful torque is only half of the maximum torque which is proportional to the adhesion of the wheels. This limit will, however, be reached only in very few practical cases.

The starting torque of the direct-current series motor is independent of the terminal voltage, whilst the torque of the three-phase and single-phase motor is proportional to the square of the line voltage. This fact is specially dangerous for starting several trains at a time on a steep grade. The single-phase commutator motors have such a high starting torque that they may do their service, in emergency cases, with 40 per cent of the full line voltage. A disadvantage with the three-phase motor is due to the fact that its breakdown torque occurs at a slip of about 10 per cent coming to standstill when overloaded and absorbing a high wattless current and developing no torque and thus being liable to be burned out in that way.

For frequent starting the watt consumption, or economy of the whole starting period, that means the efficiency of acceleration, is of utmost importance. Direct-current equipments are started by series parallel control, resistances are in circuit only for a short time as the motors accelerate a long time without resistances. In principle the single-phase motor can be started with the smallest losses, as they need no resistances. Starting transformers absorb, however, continuously a certain amount of energy and the efficiency of the motor itself is low. The most economical way of stating consists in brush shifting (Brown, Boveri & Cie). The following Tables V and VI contain a comparison of the starting losses of various systems:

TABLE V.

Total starting losses for one entire trip of an elevated train of about 160 tons, distance about 1300 m, mean speed = 30 km p. h.

	Direct current series parallel 2 motor-groups.	Three-phase.				Single-phase commutator motors (starting transformer or brush shifting).
		Simple.	Mesh-star.	Concatenated motors.	Variable number of poles.	
Mean kw hours on car	1.00	1.35	1.50	1.17	1.10	0.90 to 1.20
Mean kvA hours on car ..	1.00	1.55	1.85	1.67	1.55	1.10 to 1.50

For smaller distance the values become worse for three-phase equipments and better for single-phase motors.

TABLE VI.

Maximum efficiency of acceleration for a usual 80-ton elevated train.

Direct current.					Three-phase.				
Only rheostatic control without acceleration on the speed characteristic.	Only rheostatic control with acceleration on the speed characteristic.	Series-parallel and acceleration on speed characteristic, 2 motors.	Series-parallel and acceleration on speed characteristic, 4 motors.	Ward-Leonard voltage regulation.**	Rheostatic control throughout.	Rheostatic control ⅓ of starting time free running.	Concatenated motors.*	Variable number of poles.	Single-phase commutator motors.
43%	65%	75%	78%	70 to 75%	43%	55%	59 to 67%	55 to 65%	70 to 80%

* On the Valtellina line a value of 65% under specially favorable circumstances was measured.
** Including motor-generator.

Changing the direction of rotation is easily done for direct and single-phase current motors by crossing the connections of the armature; for high-voltage single-phase motors this ought to be arranged in the low-voltage secondary of a series transformer (Fig. 9) or a safe reversing oil switch becomes desirable. Three-phase motors may be reversed by interchanging the primary wires, whilst the repulsion motor, whose armature is only in inductive connection with the line, must be reversed either by shifting the brushes through about a polepitch (Brown, Boveri & Company) or by shifting the line connections to the stator winding by about a polepitch or by using two primary windings.

The direct current and the single-phase series motor vary in *speed* automatically about inversely proportional to the load with the effect that for variable torque the input and current consumption does not materially fluctuate, though this property is not used to its full extent in the direct-current motor, as may be seen from the following table:

TABLE VII.

Current	1.9	1.6	1	0.73	0.53	0.38 of normal.
Speed..........	0.75	0.90	1.0	1.15	1.40	1.90 for direct current.
Speed..........	....	0.70	1.0	1.30	1.8	2.5 for single-phase.
Torque.........	2.6	1.8	1.0	0.60	0.30	0.10 for direct current.
Torque.........	....	1.65	1.0	0.70	0.50	0.35 for single-phase.
Output	1.9	1.6	1.0	0.73	0.53	0.38 for direct current.
Output	....	1.2	1.0	0.92	0.90	0.88 for single-phase.

The three-phase motor and direct-current shunt motor have practically constant speeds for all loads and grades. On long lines with constant grades or on mountain railways this quality is no direct disadvantage, as the timetable is independent of the length of the trains and the motorman may quietly leave his regulating switches alone all along the trip. One may even state that the series motor in a certain sense is unable to make up for delays which usually occur with overloaded trains, in which latter case the series motors diminishes its speed. But practice proves that the motorman can easily avoid delays by making the best of the variable speed characteristic of the series motor according to the variable grades of his line. Of course on three-phase lines the main current may be interrupted for intervals. either to increase speed when descending

or to reduce speed when ascending. Concatenated motors possess in themselves an additional possibility of varying the schedule time. The inherent constant speed quality, however, means high current consumption on grades and when starting compared with series motor characteristics. Moreover the direct-current motor has very economical means for speed variation through wide ranges and the single-phase motors possess this quality even to a higher degree.

Speed variation of the three-phase motor is possible by one of the following methods:

1. Ohmic resistances inserted into the rotor circuit, the regulation of speed depends, however, from the torque used for a given resistance and is very uneconomical. Large resistances become necessary and small speeds at small torques are hardly possible. The

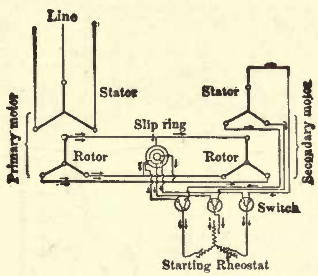


Fig. 14.— Concatenated motor connections.

higher the resistance, the more the three-phase motors acquire the variable speed quality of the series motor.

2. Concatenation of motors which has been admirably perfected by Ganz & Company. This company uses double motors in one frame (Fig. 13) uniting primary and secondary motors on one shaft needing only three slip-rings for both motors (Fig. 14). The secondary motor is never in circuit for full speed and may be specially dimensioned for concatenation. The well-known reproaches made against concatenation are: Bad power factor and bad efficiency for half speed (see Table III), increase of weight, space and heating. The maximum torque of concatenated motors is rarely more than 50 per cent greater than that of one primary motor. The starting and switching devices are rather complicated. Ganz & Company have decidedly reduced these difficulties to a minimum by building the double motors and by using a frequency of 15 periods. Efficiency and power factor are both as high as 93 per cent (without gears) for full

speed; 85 per cent efficiency and 77 per cent power factor for half speed; including gear loss the efficiency is still 80 per cent for half speed. Such an equipment is certainly not inferior to a single-phase car for full and half speeds. The Ganz motors have very high overload capacities enabling them to exert high drawbar pulls in tandem connection. The complication of the car wiring and of the starting devices has been avoided by using only three sliprings for two motors and by adopting very simple and safe liquid resistances (Fig. 15). In recent tenders Ganz & Company propose only one secondary motor for three primary motors reducing the dead weight materially.

Brown, Boveri & Cie have two heavy three-phase locomotives for the Valtellina line under construction. The two motors of each have

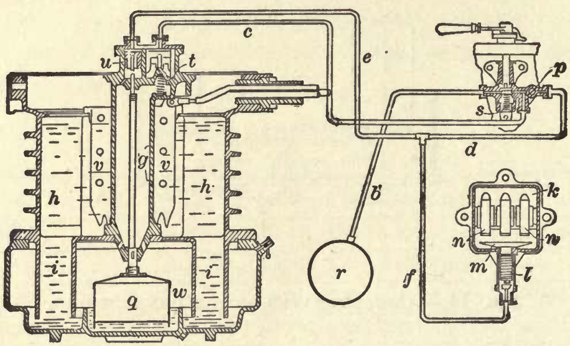


FIG. 15.—LIQUID RESISTANCE, GANZ CO.

450 horsepower and will be regulated by varying the number of poles from 16 to 8; drawbar pull 6000 kg for 37 km an hour and 3500 kg for 74 km, maximum pull for half speed 9000 kg. This scheme promises higher efficiency, higher torque for half speed, and less space than concatenation. These motors need, however, 5 or 6 sliprings per motor, if resistances have to be in the rotor circuit above and below 50 per cent of synchronism. The resistances will be metallic in this case, not liquid. The type of winding for varying the number of poles must be a multiple parallel loop winding with 2×3 terminals (Fig. 16). The winding pitch is only 60 to 75 per cent of the polepitch at the high speed and 120 to 150 per cent of the polepitch at the low speed. Concatenated motors with a different number of poles or motors with more than two numbers of poles are surely too complicated for railway work. Variable frequencies

would certainly give a very economical speed variation, but the complication and the increase of price of the central station or substation and of the line are prohibitive.

Brown, Boveri & Cie have installed a variable gear ratio on their Burgdorf Thun locomotives, which makes two economical speeds 18 and 36 km possible.

Most direct-current equipments possess series-parallel control either with two or four motor groups giving a very efficient speed variation, as the efficiency at half voltage or a quarter voltage is only

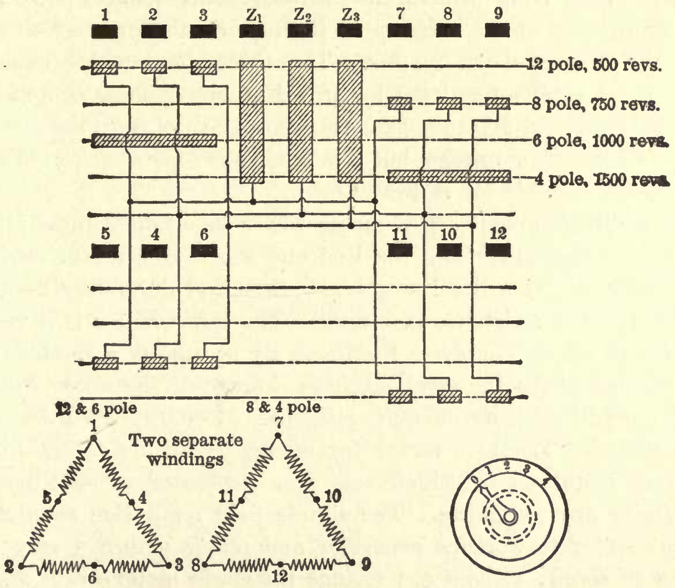


FIG. 16.— VARIABLE POLE MOTOR CONNECTIONS.

1 to 5 per cent lower than for full voltage. Double commutators may fulfill the same purpose. An increase of speed may easily be effectuated by shunting the field, in which case the efficiency is even better than for normal speed. Commutation troubles may, however, prohibit the extensive use of this method.

The single-phase commutator motor has in principle the most ideal and economical as well as the most uniform speed variation, by the use of regulating transformers in the primary or secondary circuit of the motor or by brush shifting or by varying the connections between the line and a series of taps on the primary winding. The last two methods are specially suitable for repulsion motors.

All these methods work with good efficiency and good power factor for many speeds. The continuous losses in the regulating transformers, however, decrease the total efficiency of the equipment. In fact, the single-phase regulation is not more economical than that with a four motor direct-current equipment. The losses are specially high for straight single-phase series motors using an auto-transformer, a potential regulator and balancing transformers. Series transformers, as used by Winter and Eichberg to supply only the small exciting current of the armature, are decidedly preferable to regulating transformers, and the best scheme seems to be shifting of the brushes or the shifting of the taps on the primary winding as used for repulsion motors. The three-phase motor could be very economically regulated by providing a polyphase commutator on the rotor and a three-phase transformer to change the size and phase of the rotor voltage, but this scheme is somewhat complicated and is not suitable for railway work.

If a direct-current series motor whose field connections are reversed, is separated from the line and short-circuited or switched on resistances, it will act as a *brake,* the effect depending upon the speed and the resistance in circuit. The series motor is, however, unable to return energy to the line. By arranging a small exciter which just yields the small exciting voltage of the series winding and the full exciting current, returning of energy could be easily effectuated. The best motor for energy returning is the direct-current shunt motor which acts as a generator without making necessary any switching. The simple field regulation enables the shunt motor to work as generator and motor within a very wide range of speed; without any change the shunt motor works also on resistances or as a short-circuited brake. On mountain railways the braking on resistances is, however, rarely desirable, as the resistances on the locomotives become too cumbersome and heavy (*i. e.,* 2000 kg on an 11-ton engine). If other motor cars are on the line, the downgoing shunt motor feeds the ascending. If there is only one car on the line, the energy returned will speed up the generators and will be only troublesome. One may provide resistance, in parallel with the generators, to absorb the superfluous energy, but by far the best method is to install storage batteries in the sub-stations which are charged by the descending cars.

The three-phase motor has braking qualities similar to those of the direct-current shunt motor, but throughout a very restricted range. The three-phase motor returns energy only for speeds above

synchronism, that means, within a very narrow range and the energy cannot be stored up. Braking on resistances independently from the line is only possible by an additional exciter. The range of returning energy may be somewhat increased by applying concatenated motors, but this advantage must be very expensively paid for, besides the fact exists that a short-circuited concatenated group only acts as generator between 50 and 75 per cent of synchronism and then again above synchronism. By inserting resistances in the rotor of the secondary motor this range may be slightly increased. On level lines as encountered on elevated roads not more than 10 per cent of the stored up energy can be returned by concatenated motors. On lines with many steep grades and dense traffic, the returned energy may be more and become of decided advantage.

For mountain railways the three-phase motors have been frequently used (Jungfrau, Gornergrat & Engelberg), but it does seem not to have been a complete success, as new mountain lines (Vesuvius, Opcima Triest) are not equipped with three-phase motors but with direct-current shunt motors. The main reasons are that for the three-phase motor the downgoing speed must be higher than the ascending one which is prohibited by most railway regulations and that the energy of the descending car cannot be stored up, neither of which reasons is applicable to the shunt motor. There are very ingenious schemes for perfecting the three-phase motor for steep grades. The Maschinenfabrik Oerlikon switched the motors on their Jungfrau locomotive No. 3 in the upward sense for going downward in such a way that the primary field revolved against the rotor rotation. By inserting resistances into the rotor, in which the frequency is higher than in the line, any speed between standstill and full speed may be obtained, but the resistances must dissipate twice the energy braked and the line has to provide just as much energy for descending as for ascending. The next step was to use a special direct-current exciter directly connected to the motor shaft for braking, the motor works as a three-phase synchronous generator. The A. E. G. had arranged a storage battery for the same purpose on its high-speed car. If three-phase currents must be used, the simplest scheme would be to take the compensated three-phase motor with commutator on one side and sliprings on the other, which acts as generator at will (newest Jungfrau locomotive[5] of

5. The brushes on the commutator of these motors are automatically lifted, when the locomotive is connected to the line. The speed may be cut down to 5 per cent of full speed.

Brown, Boveri & Company), though it is inferior to the direct-current shunt motor.

Those single-phase commutator motors, the armature and field of which are interconnected directly or through a transformer, may be separated from the line, and caused to work on resistances as single-phase generators of variable frequency. The return of energy to the line is possible only by rather complicated switching devices, such as changing the variable speed feature into a constant speed one or, in other words, by creating a shunt motor or a separately excited motor. This may be done practically by feeding field and armature from a transformer having a series of taps which are changed according to speed and load. (Fig. 17, Union motor.) If the repulsion motor is driven backwards, it acts as a brake; by varying the brush angle any braking torque may be produced and even at low speeds energy may be returned to the line.

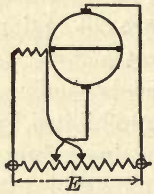


FIG. 17.—CONNECTIONS OF MOTOR USED AS GENERATOR.

For returning energy at speeds from the highest down almost to standstill, the most perfect system is a direct-current equipment with two double-commutator motors, with a combined series and shunt-field winding and regulating resistances in series with the shunt field and in parallel with the series field. For the highest speed, the four commutators are in multiple and the field weakest; for the lowest speed, all commutators are in series, the field strongest. This scheme is, however, too complicated for practical railway service.

Motors which are regularly and frequently used for braking purposes must be much more liberally laid out and they are more liable to injuries than those used simply for haulage.

The shunt motor which has several very valuable features for braking and speed variation has the great fault which rather excludes it from most railway services in that it is almost unsuitable for parallel running. This adverse criticism must be made concerning all motors with constant speed characteristics including the three-phase motor. If by chance the wheel diameters are not

identical in general, if the slip in speed is not equal or if the magnetic characteristics of two shunt motors or of two three-phase motors[6] are slightly different (not the same air-gap or not the same permeabilities), one motor takes more of the whole load than the other. It may even happen that one motor acts as generator, deriving its energy from the other which must carry the whole load, causing a break-down and throwing the locomotive from the rails. This has actually occurred on mountain railways. For emergency cases rail tongs must, therefore, be provided which prevent the derailing of the locomotive. For the shunt motor, there may be used the following remedies: Two shunt regulators may be used, one for each motor, adjusted in a manner such as to equalize the load. The adjustment is, of course, different for an ascending and a descending car, and it must be modified before reversing. A scheme installed by the Austrian Union Company on their locomotives for

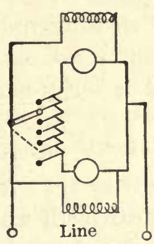


FIG. 18.—EQUALIZING SHUNT MOTORS.

Opcima-Triest seems to possess many advantages (Fig. 18). The two armature terminals of same polarity are connected by a small regulating resistance, and the lever of this resistance is grounded, the rail being the return conductor. By adjusting this resistance which takes at most 2 per cent of the whole voltage, the load in any case may be equally distributed. The position of the lever is different for motor and for generator action. The automatic breaker in the trolley circuit cannot be used for avoiding overloads, as the current does not flow to the line and as the armature circuit is not allowed to contain a circuit breaker, as it would render emergency braking very dubious. Brown, Boveri & Cie arrange a friction clutch between each motor and the axle, which transmits only a certain maximum torque. The simple remedy of using only *motors in series* is not to be recommended as on steep lines it happens that

6. For three-phase motors that means different magnetizing and different short-circuit current.

one wheel slips and the other stands still, in which case the former motor is subjected to the whole voltage and may burn out.

Cars with direct-current equipments may be run on lines with variable voltage, if the motors are connected only in series on one part of the line and only in multiple on the other, or by adopting double commutator motors. The trolley line voltage of three-phase and single-phase cars may be varied at will, if a stationary transformer is provided on the car, which transformer, however, increases the weight of the equipment considerably. The Austrian Union Company is just completing a suburban single-phase line, starting from Innsbruck, which is fed at 400 volts inside the town and at 2700 volts outside. Single-phase cars may even be run over direct-current tracks, though a good single-phase motor usually is a pretty bad direct-current machine; for the repulsion motor this is a specially bad case. Moreover the primary and secondary motor voltage rarely agrees with the direct-current line voltage and a special set of starting resistances must be provided, or the single-phase equipment must use rheostatic control, which is very uneconomical. Best is series-parallel control in this case.

Motor Gearing.

In most cases the motors drive the car axle by

1 a *single gear* of cylindrical tooth wheels with ratios of 1:1 to 1:5 which withstand the wear of 8000 to 200,000 train-km. In few cases one finds

2 *cogged wheels* (Alioth) or double and treble threaded *worm gears* (Maschinenfabrik Oerlikon), which in some cases allow a better disposal of the available space. For very low speeds *double gear* becomes necessary, *i. e.,* Jungfrau and other mountain locomotives.

3. The *direct coupling* of motor and axle may either be

(a) *rigid* (Central London, Siemens & Halske high speed car, new locomotives for New York Central) or

(b) *elastic,* by means of a hollow shaft and a flexible coupling (Heilmann Locomotive, A. E. G. high speed car, Valtellina locomotives of Ganz & Company). The rigid connection of the armature on the car axle has up to the present not been a complete success, but the method with the hollow shaft and coupling is decidedly complicated and entails the waste of much precious space. Siemens & Halske support the frame of their rigidly connected motors from the truck by means of springs, by which the bearings are pressed

against the axle from below, an oil cushion on the upper half of the bearing boxes damping vertical shocks of the frame. From Fig. 19 one may get an idea of the design of the Valtellina motors for 250

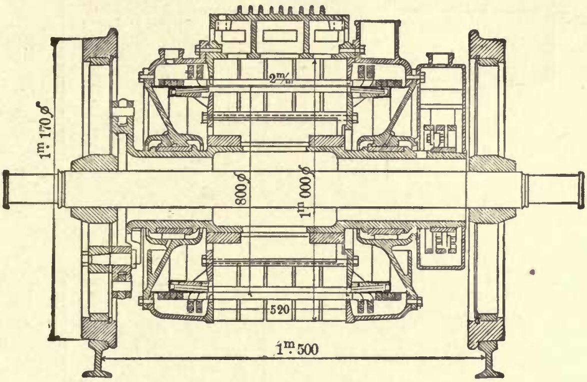


FIG. 19.— VALTELLINA GEARLESS MOTOR.

horse-power, 300 revolutions, 3000 volts, with a hollow shaft and a flexible coupling. The new 550-hp motors of the General Electric Company are rigidly fixed on the axle, but the frame may freely move in the vertical direction, as the motor has only two poles, one at each side, and the pole shoes have plain vertical surfaces. For motors mounted on the car axle, special care is necessary to exclude oil and dirt from the motor windings.

4. Driving by *cranks* and *connecting rods,*— well known from steam locomotives — was probably first proposed for electric locomotives by Eickemeyer, and first used by Brown, Boveri & Cie. The location of the motors above the axle is decidedly facilitated by this mode of driving. Very disagreeable vertical and other movements and shocks, such as are incident to steam driving, can hardly be avoided when this construction is used. Ganz & Company have laid out a special arrangement for their new Valtellina locomotives

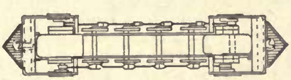


FIG. 21. LOCOMOTIVE WITH CONNECTING RODS.

(Fig. 20), the crank turning point being supported in such a way as to allow vertical movements. The General Electric Company possess a patent on the arrangement (Fig. 21), in which two double

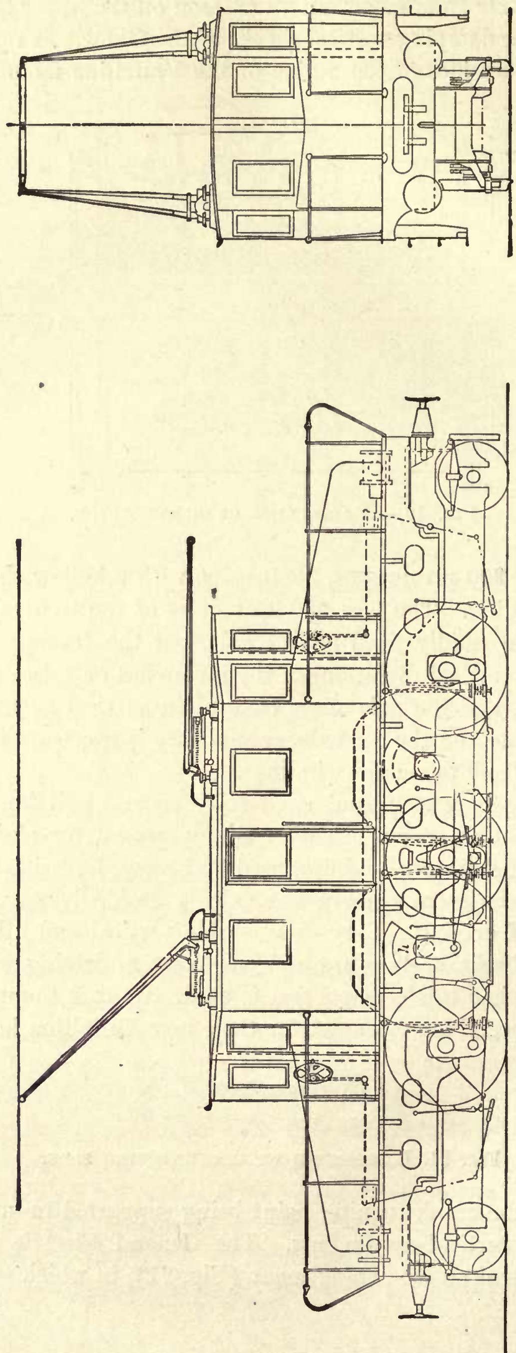


FIG. 20.— VALTELLINA LOCOMOTIVE.

commutator motors are mounted at the end of the locomotive and four axles are joined by cranks and connecting rods.

Starters.

For starting are used

(a) Metallic or liquid resistances combined with series parallel control;

(b) Transformers or autotransformers with taps or potential regulators,— mainly for single-phase motors;

(c) Brush shifting for repulsion motors (Brown, Boveri & Cie). The last method is undoubtedly the cheapest.

Regulating transformers for single-phase motors are heavier and more expensive than starting resistances, even if high iron inductions (15,000 per cm^2) and high copper densities (3 to 5 amp. per mm^2) are adopted. They should be submerged in oil or artificially cooled by compressed air. If series transformers (Fig. 8) are used for the armature alone, the size and weight are materially reduced. The heaviest are the potential regulators which must be provided with a short-circuited coil to neutralize the cross-field or self-induction of the armature. They allow, however, a very steady regulation, and avoid all contacts liable to spark; the higher the line current, the smaller is the range of voltage control. The main difficulty in the design of the usual regulating transformers with taps is due to the necessity for a reliable switch dial which works sparklessly. The best scheme seems to involve a solid snap switch which interrupts the current for a moment, when jumping from one tap to the next thus avoiding all auxiliary contacts and the short-circuiting of coils and eliminating the use of resistances or inductances.

For various reasons three-phase starting resistances must be heavier and more voluminous than direct-current starters. To this is probably due the fact that liquid resistances have been thought more desirable for three-phase than for direct-current railways. Though at first sight a liquid resistance seems to be mechanically much poorer than solid parcels of nickeline strips or castiron grids, the dimensions of which may be very much reduced by forced air cooling (Jungfrau line) or by placing them into oil tanks, the designs of Ganz & Company and those of the A. E. G. high-speed car are of practical interest, and the first mentioned

design[7] (Fig. 15) has operated satisfactorily for years. The principle involved in their construction consists in using stationary electrodes within a tank into which the liquid is forced either by air pressure or by a rotating pump. The time consumed in starting may be varied by regulating the air pressure or by adjusting a throttle valve (Fig. 15). The electrodes consist of solid parcels of iron sheets which may be readily replaced. For frequent starting and shunting purposes, the liquid tanks must be very liberally dimensioned; it is desirable that the motorman control the resistance according to a main current ammeter, to avoid current rushes. The outer surface of the tank is provided with cooling ribs. The overload capacity of liquid starters is very high, as when the water is evaporating, an immense amount of heat may be absorbed. There is, however, the drawback that the water level may oscillate and that the evaporated water must regularly be replaced (2 liters on 500 km for the Valtellina line). On very cold days freezing is possible. To avoid a heavy current rush before short-circuiting the liquid starter, it is necessary that the electrodes have such a shape as to finally reduce the resistance to a value less than that of the armature.

The starting switches may be,

1. *Cylindrical controllers* with contacts for reversing and series-parallel control, and for the control of resistances or transformer coils, sometimes provided with flat dials at the lower end for field regulation.

2. *Multiple unit control* with a series of single switches actuated by electromagnets or by compressed air pistons.

3. *Liquid starters.*— For small inputs, the cylindrical controllers are in almost universal use. For three-phase equipments, they become heavier and more voluminous, on account of the increased number of contacts, which number may be somewhat diminished by using two-phase rotors. The multiple-unit system has been developed for direct current by the General Electric Company (electromagnetic switches), by the Westinghouse Company and the Siemens Schuckert Werke (electropneumatic control), for single-phase cars by the Union E. G. Berlin, the system resembling very much the direct-current control of the G. E. Company. The electromagnets, however, must be

7. Fig. 15 shows the original design of the Ganz rheostat which has been changed somewhat in its details; p is the throttle valve, k the short-circuiting switch of the rheostat.

laminated, and for the primary circuit, high-tension oil switches must be used. As alternate-current electromagnets are known to have various bad qualities, it seems to be a good plan to propose direct-current control from a small storage battery or electropneumatic control for single-phase cars. For three-phase equipments multiple-unit control has never been used or proposed,[8] on account of its being rather complicated. Moreover the tendency of three-phase railways is toward locomotives and not toward the use of a series of motor cars in a train. On account of the many wires and contacts for three-phase current liquid starters with pneumatic control have come to the front, as already stated. The liquid resistance does away with the great number of contacts and the sparking troubles of switches for heavy currents, allowing a very steady regulation and occupying only a moderate amount of space. Several single-phase or direct-current motors in multiple may be equipped with one common starting resistance if desired, whilst this arrangement is not possible with three-phase motors, unless the relative position of all parallel rotors is *continuously* identical, which condition seems impossible to be obtained. When this is not the case, the rotors may be partly short-circuited by the cross-connections.

In the following Table VIII I have tried to make a comparison of the weight of various starting devices.

8. There are several patents on polyphase multiple control granted to the G. E. Co. four years ago.

TABLE VIII.

a. *Direct current.*

Builder.	Motors. Volts.	H. P.	Weight, kg.	Weight of starting devices in kg.
Krizik Prague....	2x650	4x30	4x935	Entire electric equipment per car without motors: 1,560.
G. E. Co..........	500	1x27	700	1 controller and resistance: 150.
Alioth............	500	2x31	2x770	Entire electric equipment without motors: 960.
Alioth............	500	4x38	4x890	Entire electric equipment without motors: 3,600.
Westinghouse....	500	2x55	2x1,360	2 controllers and resistances: 660.
G. E. Co..........	500	2x65	2x1,600	2 controllers and resistances: 600.
Alioth............	500	2x65	2x1,350	Entire electric equipment without motors: 4,100.
G. E. Co..........	500	2x80	2x1,800	2 controllers and resistances: 700.
Thury............	4x600	4x125	4x3,600	Entire electric equipment without motors: 6,600.
Westinghouse....	500	2x150	2x2,400	2 controllers and resistances: 750.
G. E. Co..........	600	2x165	2x2,400	Weight of whole control apparatus: 1,000 (multiple unit).
Westinghouse....	600	2x150	2x2,400	Weight of whole control apparatus (including small battery): 800 (multiple unit).

b. *Three-phase currents.*

Brown, Boveri....	500	2x25	2x830	Entire electric equipment without motors: 1,500.
Brown, Boveri....	750	2x150	2x4,000	2 controllers and starting resistances: 2,000.
Siemens & Halske	10,000	2x200	2x4,100	Entire electric equipment without motors: 8,800 (metallic resistances).
Siemen & Halske.	10,000	4x250	4x4,000	Metallic resistances 5,000, controllers 4,800, transformers for 10,000 | 1,000 volts: 12,000.
A. E. G...........	10,000	4x250	4x3,200	Liquid starters 4,800, transformers 6,400.
Ganz & Co........	3,000	2x600	2x12,500	Entire electric equipment without motors: 7,000 (liquid starters).

c. *Single-phase current.*

Finzi............	500	1x27	1x800	Transformer 300.
Union............	2,700	2x50	2x1,240	Transformer 2,700 | 400 volt: 630 kg (oil type), regulating transformers: 2 × 315 kg.
Union............	6,000	2x100	2x2,360	Regulating transformers 1,100 kg, whole electric equipment without motors 1,800 kg.
Oerlikon.........	14,000	4x145	4x3,000	Transformers 5,600 kg, apparatus and switches 800, trolley 1,200.
Oerlikon.........	14,000	4x200	4x3,400	Transformers 8,400 kg, apparatus and switches 900, trolley 1,200.

For the repulsion motor with brush snifting no special starting devices are necessary.

For operating whistles and brakes, electricity is not directly applicable, and, in most cases, compressed air must be used for this purpose. The air brakes and the main controllers should be so interconnected that applying the brakes instantly interrupts the main current. The air compressor should be driven electrically and should run noiseless, which latter condition seems to be most easily obtained when slide valves are used. On steep grades there should be provided electromagnetic rail brakes, or a braking rack should be placed along the rails. To avoid derailing on mountain railways, rail tongs are desirable. In order to eliminate the possibility of racing on steep grades, there should be provided a device which prevents the motorman's leaving his car or train if he has not first put the controller-handle on the short-circuit braking point.

Although universally used, the scheme of lighting the trains directly from the trolley line is a bad one. Periodicities below 40 give a flickering light, unless very low voltages and thick filaments are used. The question of train lighting is, however, not so important as to render useless a system which, though defective in this one respect, is first class in all others, it being possible, in any event, to provide for lighting the train from some source independent of the trolley circuit.

Current Collectors and Line.

The problem of collecting current from the line is one of the most difficult in electric traction. While direct-current and single-phase equipments using the rails as return require but a single conductor, three-phase and certain other three-wire cars necessitate at least two-line wires, which drawback to such equipments in some cases is so serious as to prohibit their use. The two conductors may be installed either above the center of the line beside each other in the same height or in different heights, or beside the line one above the other, the current collector sliding from the side, or one wire may be on each side of the line (Fig. 22). The lateral current collection avoids the oscillation of the current collector, arising from the deflection of the wire, but if the wires hang above each other, short-circuits may easily occur. As far as my experiences go, there seems to be no difficulty in collecting current for single-phase lines for voltages up to 6000. For three-phase lines the limit, as derived from the experiences on the Valtellina line with humid tunnels,

sharp curves and steep grades seems to be 3000 volts. For equal line voltage the voltage drop of the line which influences very much the starting torque of alternate-current motors is much greater for three-phase and single-phase currents than for direct current and on account of phase displacement, the equivalent current is also higher. The increase of voltage drop is the higher, the higher the frequency. The resistance of the iron rails for alternating current amounts to between 3 and 15 times the value for direct current on account of the skin effect. A high voltage drop in the rails causes electrolytic effects for direct current and

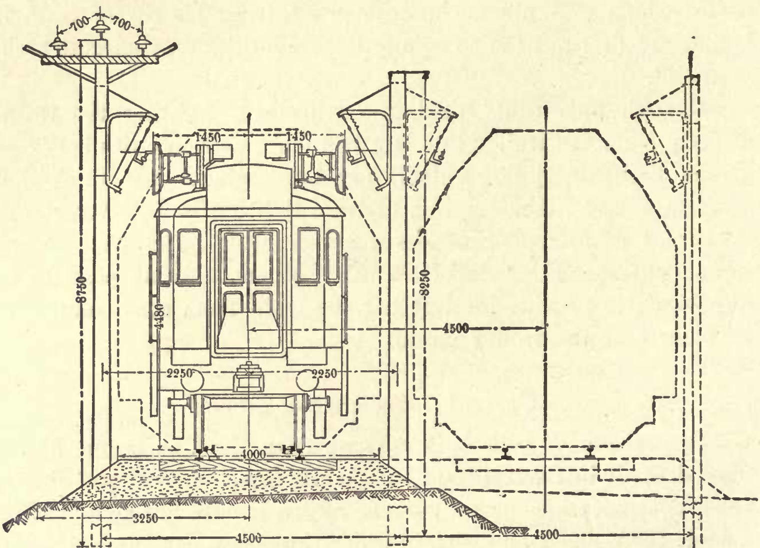


FIG. 22.— HIGH POTENTIAL OVERHEAD CONSTRUCTION OF SIEMENS & HALSKE.

telephone or telegraph disturbances for direct and alternate currents. For this reason special return wires may become necessary (fourth rail), which must be frequently connected to the main rails, and which, for alternate currents, should be as close to the other trolley wires as possible. Kapp proposed to place boosting dynamos or transformers between two consecutive rails at various spots. The Maschinenfabrik Oerlikon is using a separate return wire along the rails and puts the boosting transformers into this special wire, the primary of the transformer being in the overhead conductor. In this way the voltage drop of the return wire which

is regularly connected to the rails is reduced to naught and the drop is transferred to the overhead wire, the drop of which is correspondingly increased. If high trolley voltage or the boosting scheme of Oerlikon is used, railbonds are no longer a necessity; they are, therefore, omitted in a new single-phase line of the Austrian Union Company with 2700 volts.

The current collectors used nowadays are:

1. The *trolley wheel* with overhead conductor consisting of a circular or an 8-shaped profile-wire, suitable for about 200 amp. voltages below 1000, and speeds not exceeding 80 km an hour. The trolley wire may hang just above the line or on the side of it (lateral trolley), as the trolley arm is hinged upon a vertical bolt; the height of the wire above the line may also vary considerably. A disadvantage is the hammering of the wheel against the wire and the frequent derailing, which may be somewhat reduced by using

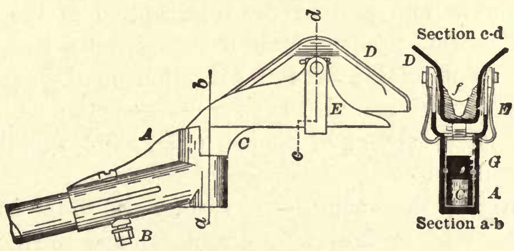


FIG. 23.— TROLLEY SHOE.

very light and elastic trolley arms, the movements of which may be damped by various springs or air and oil cushions. For currents greater than 200 amp., two trolleys may be adopted.

The wheel may be replaced by a sliding shoe on the end of the trolley arm (Fig. 23), the inside of which may be covered with aluminum (Jungfrau railway). The ability to collect current is increased in this way, but the deterioration of the wire is augmented.

2. The *sliding bow* consists of a tube of brass or aluminum containing a V-shaped groove and stands with axis perpendicular to the trolley wire. To get a larger surface of contact, Brown, Boveri & Company have given a triangular cross-section to the bow (Fig. 24), one plain surface of which is continuously on the wire. The inside of the tube may be filled with grease. The bow may carry 100 amp. for voltages up to 10,000 or 200 amp. for low voltages; sliding on two overhead wires 300 amp. may be safely

collected at 1000 volts or less. The line equipment, especially the overhead switches, are much simpler for the bow than for the trolley wheel; there is no derailing. The bow automatically adjusts itself for forward and backward movements which feature is very important for shunting. The bow is probably the best cur-

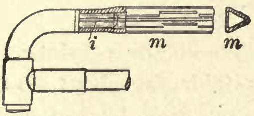


FIG. 24.— SLIDING SHOE OF BROWN, BOVERI & CO.

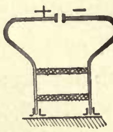


FIG. 26.— DOUBLE BOW.

rent collector devised for high speeds, in which case it may be as light and elastic as possible; the pressure on the wire should not exceed 2 to 4 kg, and several springs acting after each other must neutralize shocks and prevent the interruption of the contact by the bow. The wind pressure must be compensated by wings. The satisfactory result of the current collection on the experimental[9] Siemens high speed car at 10,000 volts and 100 amp. per wire is due to the lateral sliding of the bow (Fig. 25[10]), avoiding thereby the movements due to the deflection of the wire, to the great elasticity produced by three consecutive springs and to the small weight of the cross-bar of the bow (650 grammes) and to the *very* small pressure of only $2\frac{1}{2}$ to 3 kg; on three-phase lines one may apply either two separate bows beside or behind each other or *one* bow the cross-bar of which consists of two insulated pieces (Brown, Boveri & Company) (Fig. 26).

3. Most of the good qualities of the bow are also to be found in the new original current collector of the *Machinenfabrik Oerlikon* (Fig. 27) consisting of a *curved rod* of brass tubing sliding on the lateral overhead wire from above, when running on the free line. At stations and in tunnels, or wherever it is desired, the rod makes contact from below *exactly* as the bow. The turning of the rod through an angle of nearly 270 deg. is effectuated either by hand or pneumatically. There are 2×2 rods on each locomotive, which may collect the current from either of the two wires on each side of the line. In this way one wire may be repaired,

9. The treble bow is of course much too cumbersome to suit for regular service.
10. Consisting of a brass tube with aluminum filling.

while the other is working. The repairs of the wire and of the current collector are quickly made and do not necessitate the use of a turret car which blocks up the line. Without any serious sparking, the rod collects full current while the locomotive travels at full speed from a section with 15,000 volts to a line section which is interrupted by the semaphore.

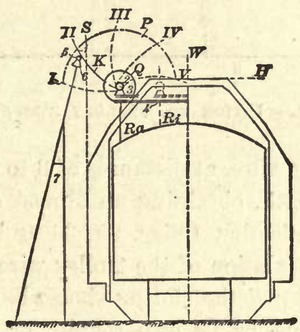


FIG. 27.—OERLIKON CURRENT COLLECTOR.

4. The *cylindrical roller collector* somewhat resembles the one of the bow type, the cross-bar consisting, however, of a rotating roller usually running on ball bearings. On the Valtellina locomotives this roller for 3000 volts and 200 amp. per wire makes 4000 revolutions a minute and consists of two copper tubes or two steel tubes electrolytically covered with copper, insulated from each other by impregnated wood. The tubes have to be replaced after a service of about 15,000 train-km. There is one roller collector for forward running and one for backward movement (Fig. 20),

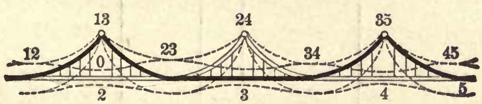


FIG. 28.—GANZ & CO. TROLLEY SUSPENSION.

each being controlled by compressed air. The roller is usually heavier and less elastic than the bow. To avoid the hammering effect of the deflection of the wire, Ganz & Company propose to use two trolley wires (Fig. 28) which cross each other, the support of one wire being at the spot where the other has the deepest deflection.

Overhead wires should not be fastened rigidly but in an elastic manner, to avoid break-downs of the wires by the hammering effect of the collector, which effect increases with the speed. The Union Company fastens the trolley wire for their single-phase lines

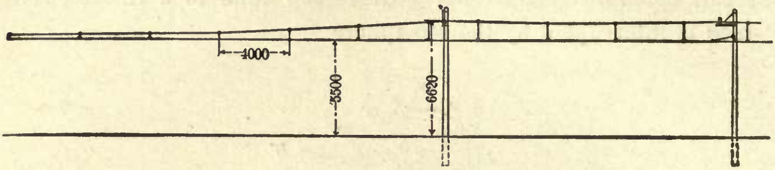


FIG. 29.— UNION CO. TROLLEY SUSPENSION.

to a special suspension wire, at distances of 3 to 4 metres, by vertical wires of variable length, obtaining an almost straight trolley wire with unnoticeable deflection (Figs. 29, 30 and 31). For voltages above 1000 double insulation of the trolley wire is to recommended.

5. From the *third rail* the sliding shoe which is usually pressed on the rail from above by its own weight, or by springs or pneumatically from the side or from below, may collect currents of

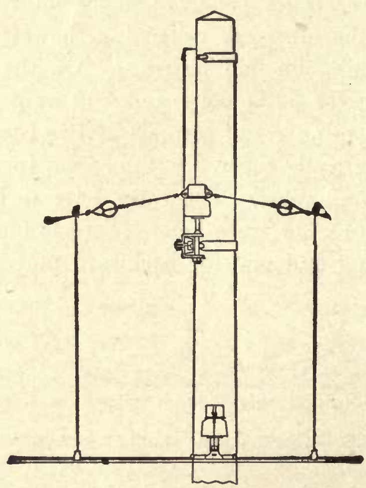


FIG. 30.— TROLLEY SUSPENSION.

more than 2000 amp. For heavy currents this is the cheapest and most durable scheme yet proposed, though for alternate currents, the increase of the resistance by skin effect is very objectionable. The main difficulty which makes the third rail prohibitive for

three-phase lines is the necessity for the thorough protection of the live rail, mainly at stations. It is, however, possible to cover the third rail at stations by wooden boards leaving only a narrow crevice for connection with the shoe (Baltimore & Ohio Ry). If the shoe projects laterally from the car, the third rail may easily be protected by overhanging boards in such a way as to eliminate danger to operators and officials when crossing the rails. Too much protecting, however, prevents rapid inspection. On the Fribourg-Murten line (Switzerland) the third rail was allowed only for the free line, at the stations two bows and two overhead wires were prescribed, complicating the system materially. During the erection of the third rail, special care must be taken to allow for heat extension and to prevent the movement of the rail. Overhead

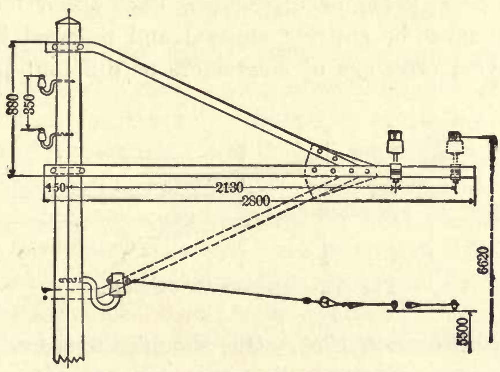


Fig. 31.— Trolley suspension.

conductors for heavy currents above 500 amps. would necessitate very expensive framework and a conductor having the shape either of a usual rail or of a U iron or two Z irons. The elevated railway of Elberfeld is using such an overhead rail and the Baltimore & Ohio Ry. formerly used an overhead tube which, however, has been discarded.

If the same car has to run on tracks with different voltages, two different kinds of current collectors must be provided. On the line already mentioned with 400 and 2700 volts single-phase, the Austrian Union Company has installed a high bow for high tension and a low bow for low tension. The trolley wire at the end of the low voltage track is gradually raised and the low bow automatically leaves the trolley wire.

Disagreeable disturbances are caused on trolley wires and third rails by *ice and sleet.* A mechanical remedy consists in using scrapers and metal brushes which, however, deteriorate the conductor; it is also not always sufficiently effective. On heavy third rails may be applied certain chemicals, as calcium chloride, as they readily melt all ice and sleet, the soft mass being easily swept away by brushes on the motor car. Electric heating, though somewhat expensive, has also proved a success, as on the Burgdorf Thun railway. The line is short-circuited with low voltage only as long as is necessary to soften the ice; the sliding bow sweeps it away afterward. A thin coat of varnish on the trolley wire may prevent the formation of ice without disturbing the collection of current. It is noteworthy that ice not only depends from the lower side of the wire, but it forms on the upper side also.

In overhead switches of three-phase lines either both wires or at least one must be entirely omitted and replaced by insulated pieces, to avoid crossings of conductors of different phases (Fig.

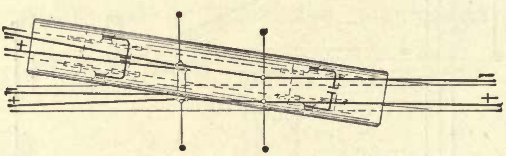


FIG. 32.— OVERHEAD SWITCH.

32, of Brown, Boveri & Cie). One should, therefore, always provide at least two current collectors on the motor cars, spacing them at a distance somewhat greater than the length of the overhead switch. It is bad practice to be compelled to pass all switches without current, as it necessitates special attention on the part of the motorman and means low acceleration and very inconvenient shunting. It is advantageous to have at least one phase running all through the switches (Fig. 32), as in this case the motors continue to work as single-phase machines; starting is, of course, excluded. On third-rail tracks there occur similar interruptions along street crossings; at least two sets of shoes are, therefore, necessary at each end of the car. The intersecting roads should cross at a small angle, and the third rail should continue on different sides of the line beyond the crossing.

The following characteristic features seem desirable in a current collector for universal use: Running and shunting in both

directions must be possible without reversing the position of the collector. There must be neither hammering of wire nor breaking of contact at high speed. The current collector must not be able to destroy the line construction and must be incapable of being derailed during service. Repairs of the collector and of the line must be quickly made without interrupting the regular service. This necessitates either the simple direct-current system for voltages less than 1000, or for high voltage single-phase railways two separate trolley lines have to be erected on both sides of the line (Maschinenfabrik Oerlikon). Simplicity of the line and of the switches which must be crossed with full current on dictates the use of only one current-collecting conductor. High voltages from 3000 upwards seem absolutely necessary for long lines.

Central Stations and Sub-stations.

The generators and transformers for single and polyphase railways must be designed for the apparent input of the railway motors, that is, for the kilovoltamperes which are considerably higher than the kilowatts. The low power factor of the current entails a much higher voltage drop than current at unity power factor, which feature is specially bad for alternate-current motors so sensitive to voltage variations. The mean power factor on three-phase lines is sometimes as low as 50 per cent, and during starting it is even lower for single-phase motors. Single-phase generators and transformers are larger and more expensive than those of the polyphase type. It is, of course, possible, or even necessary, to use two-phase generators for single-phase lines, but both phases will always be far from equally loaded. Generators and sub-stations must be able for moments to deliver the maximum output, which in some cases may be more than 10 times the mean value on long lines with light traffic, but which in other cases may fall down to only 50 per cent above the mean value. If in the sub-stations of direct-current railways storage batteries are provided, the converters and generators may be very much reduced in size and price, having to yield only mean values. Storage batteries are, however, expensive in first cost and in service, and their efficiency is only about 75 per cent, but they decidedly increase the reliability of the service and in most cases reduce the first cost of the plant and materially diminish the operating expenses. In three-phase or single-phase plants storage batteries would be possible only by installing rotaries which

would have to work alternately as direct and as inverted converters, a very complicated scheme. By using very heavy fly-wheels and a great speed variation of the prime movers between no load and full load, the power rushes may be kept away from the prime movers but not from the electric generators and transformers. The dropping of the speed in the central station when trains are started is quite favorable to alternating currents, as the periodicity is reduced thereby. A somewhat better scheme would be the use of high speed fly-wheel sets, electrically driven and influenced by the load in such a way as to be charged in the shape of kinetic energy, when the line runs at light loads, and discharged when much energy is needed on the line. Such sets must have a wide range of speed variation; but up to the present they have been successfully built only for direct-current net-works.

As long as direct-current pressures have to be kept lower than 1000 volts, the most serious drawback to direct-current equipments, besides the expensive feeders and trolley lines, is the large sub-stations with rotating machinery. These latter cost more for installation and maintenance than stationary transformers of the self-cooled oil type, which type is best for railway service up to 500 k. v. a., as they easily give 4 to 5 times the normal output for a short period, if the normal maximum voltage drop is not higher than 1½ to 2 per cent. Rotaries for low periodicities (10 to 25) with a good reactance voltage or provided with auxiliary commutation poles should stand a momentary overload of 100 to 200 per cent. But, as a matter of fact, there are many cases in which even for long lines direct-current railways are not much more expensive in first cost than single or three-phase equipments, and the operating expenses are very often in favor of direct-current, the substations amounting only to about 15 per cent of the price of the whole plant. By increasing the direct-current voltage or by the invention of reliable stationary converters for transforming three-phase into direct current, the conditions would even become more favorable to direct current.

As the voltage drop influences considerably the torque of all alternate-current motors the generators and transformers must be so designed as to give a very good voltage regulation at inductive loads. The Valtellina generators yield a short-circuit current six times the normal current with full load excitation and are guaranteed to stand that current for two minutes. Compound generators or even those of the overcompounded type would be very desirable for single

and three-phase lines, but there is no satisfactory and reliable type on the market; all of the known compensated generators are complicated and are surely not able to successfully withstand the severe conditions of railway service. There are, however, excellent automatic voltage regulators on the market, which work nearly instantaneously, and which seem to be well adapted for railway plants (Tirril regulator of the G. E. Company and the Thury regulator of the Cie de l'Industrie El. Geneva).

For equal trolley voltage and equal voltage drop, the sub-stations must be closer together for alternate than for direct-current equipments. For a dense traffic and direct-current voltages above 1000 it is often better practice to use exclusively central stations, eliminating the expensive sub-stations. On main lines the transmission voltage ought to be as high as possible, 60,000 volts according to the present development of the art, to get a uniform load. The trolley voltage of 3000 to 8000 may be transformed in substations at distances of 30 to 60 km which may be increased to 100 or 150 km for 15,000 volts. For the production of high voltage direct current at 1500 to 4000 volts, low speed generators must be used, preferably two or more in series, or machines of the double commutator type may be employed. These arrangements facilitate also the connection of the neutral wire for a three-wire net-work. Rotaries for voltages above 1000 should be fed by alternate currents of low periodicity, say 10 to 15; double commutators and auxiliary commutating poles may be desirable.

Years ago direct current was declared entirely unsuitable for long lines and heavy traffic; today many give up three-phase and direct current to use only single-phase of which we know very little as yet, from a practical standpoint. I believe that all three systems may counterbalance each other; yet each of them lacks some desirable features. Direct current is restricted to low train voltages and needs expensive sub-stations; three-phase railways make two trolley wires necessary, are very sensitive to voltage variations and badly overload the central stations; the last two disadvantages are more or less applicable also to single-phase lines, which possess the additional troubles on the commutator and the low efficiency. None of the systems offers the possibility of running through parts of the line independently of an outside current source. Up to the present neither of the other systems is known to be as reliable and safe as the direct current. The first costs of the car equipments are throughout higher for three and single-phase than for direct

current; for equal voltage the line equipment is cheapest for direct current; but the possibility of using high trolley voltages for alternate currents shifts the result essentially in favor of single and three-phase currents, mainly of the former. The sub-stations are more expensive for direct current, while the central station costs least for direct current. As to the operating expenses, the cost of attendance for the sub-stations is unfavorable to direct current. The result of serious comparisons between the systems shows usually a difference in first cost of not over 10 to 25 per cent and the difference in operating expenses is even less and in many cases the results are in favor of direct current. Between three-phase and single-phase there is no essential difference as to price, single-phase having the advantage of simplicity and the possibility of higher trolley voltage, but possesses the disadvantage of needing a commutator.

For long lines and heavy trains with low accelerations, three-phase equipments will always have good chances, especially if through trains are arranged and all shunting is done by special engines. On urban and suburban lines, direct current is entirely sufficient and satisfactory, though a reliable single-phase motor will be a hard competitor, as single-phase equipments may be arranged to suit long and short lines at the same time.

Hundreds of thousands of motor cars with direct-current equipments, at voltages from 500 to 1000, manufactured by all important electric concerns of the world, at the head of which the General Electric Company, Schenectady, must be mentioned, have been for many years in regular and highly successful service on street railways, on elevated and underground railways, on mountain railways, on suburban and interurban lines, with heavy and light traffic, with low and high speeds. Most of them with motor outputs from 20 to 300 horse-power have also proved to be a decided financial success. But even the heaviest locomotives of the world with pretty high speeds will successfully operate with direct-current equipments at 750 volts, I mean the New York Central engines of 2200 horse-power and the hauling locomotives of 2 × 1000 horse-power of the Baltimore & Ohio Ry. for 1600-ton trains. There is also a high voltage direct-current line in regular service in France built by Thury at 2 × 1200 volts and with 4 motors of 125 horse-power per locomotive.

Three-phase equipments have been adopted on two or three street railways, on several mountain railways and on two main lines, viz.,

the Burgdorf Thun line (Brown, Boveri & Company) with 200 to 300 horse-power per train, speeds up to 36 km and accelerations of 0.24 m (per sec.)[2] besides that on the Valtellina Railway in Italy where locomotives are running now with 1200 horse-power and speeds up to 64 km with accelerations of 0.16 m (per sec.).[2] Besides the experimental work on the Berlin Zossen line, all the three-phase railways are due to Brown, Boveri & Cie and Ganz & Company. The last concern has orders for two more three-phase lines in Canada and in England with 1000 and 600 volts at the trolley wire and locomotives of about 200 horse-power.

There are only a few single-phase railways in service as yet. There is the short track on a suburban line of Berlin (Spindlerfelde) equipped by the Union Company with motor cars having four motors of 120 horse-power each, 6000 volts at the train and pretty high acceleration. Moreover there is the Stubaithalbahn in Austria, a tourist line with light traffic, also equipped by the Union Company with motor cars having two motors of 50 horse-power each and 2700 volts on the trolley. Another line equipped by the same concern with similar cars will operate in Belgium (Borinage). The Siemens-Schuckert Werke are building the Oberammergau Railway in in Bavaria, a short, steep line with light traffic, and the Westinghouse Company has two interurban lines of over 250 km total length under construction (Fort Wayne and Indianapolis). Many single-phase projects and tenders have been worked out and offered, mainly for urban, suburban and interurban lines, with motors from 30 to 150 horse-power, and the Union Company goes even as high as 300 horse-power. Thus it may be expected that the next few months and years may tell us many a practical tale and may prove to be markstones in the development of long distance and heavy electric railways.

APPENDIX.

While this paper is being printed, various facts, mainly relating to single-phase traction, have become known which should be mentioned here. Besides the various heavy three-phase locomotives with motors in concatenation and with variable number of poles, there has been placed an order to equip a locomotive with four single-phase commutator motors of the Finzi type, each motor for 100 horse-power at 15 cycles and 300 volts.

Speaking of starters, I mentioned that Brown and Boveri are perfecting a single-phase system using the repulsion motor and doing all regulation by brush shifting. This scheme, proposed by Max Deri, is described in the Swiss patent 28964. The motor has two systems of brushes, and for a bipolar motor four brush sets. One system has its axis coinciding with that of the stator field; the other system is shifted by an angle which is nearly zero at standstill and is increased corresponding to torque and speed. Both systems may be shifted, one alternately remaining in the field axis; starting, regulating and braking being effectuated in this simple way. One brush set of one system is directly connected with the nearest set of the other system.

The Lahmeyer Company of Frankfort is also developing a compensated repulsion-motor for railway purposes. On the commutator, supposed bipolar, there are four brush sets 90 degrees apart from each other. The first and second brush set is interconnected by a short-circuit and the third and fourth as well. The connecting points are closed on the secondary winding of a regulating transformer whose primary is fed by the line in multiple with the field winding, the secondary windings having a series of taps. The working conditions are similar to those of the compensated motor Fig. 7.

In a great many cases alternating-current lines will be extensions of existing direct-current networks, giving rise to these two important conditions:

1. The alternating-current motors must be fed from the existing high-tension three-phase transmission line at 25 cycles. As to this point, there is no difficulty either for three-phase or for single-phase car equipments; in the last case it is advisable to transform the three-phase into two-phase currents by conveniently connecting up the line transformers, and to feed the trolley line sections alternately by the two phases.

2. The more difficult condition is to equip line and cars in such a way that all vehicles may be equally well fed by high-tension alternating current and direct current. The fulfillment of this condition is the most characteristic feature of the recently-opened Schenectady extension line of the General Electric Company, which I need not to describe in detail here. It is interesting that this company with the widest and most thorough experience in electric traction has given up the repulsion motor to use the series motor with a distributed compensating winding shifted by half a pole-pitch against the main field winding and in series with the main current. This auxiliary winding resembles the well-known Ryan winding of direct-current machines, neutralizing, as far as I see, the armature cross ampere-turns as well as the reactance voltage of the short-circuited coils. The motor has no projecting poles but a two-phase winding equally distributed in slots. Both the 600 volts direct current and the 2200 volts alternate current are collected by trolley wheels, the high-tension by a lateral trolley, both trolley wires being on the same poles. The 50-hp motors for 200 volts across terminals seem to have an air-gap of 2 mm or more. The step-down transformer, which is not used for regulation, is cooled by air draught. The total motor efficiency as a single-phase motor is smaller by 5 per cent than in direct-current working; the power factor is 90 to 95 per cent. The kilovolt-amperes input for a complete run on the suburban line are nearly 50 per cent higher for alternating current than for direct current. Starting and regulation are effectuated for both currents by the same series-parallel control using the same five resistances and the same controller, the efficiency of acceleration being somewhat smaller than for voltage control.

Ganz & Company are just building a three-phase line in Canada where, as I am informed, the same condition has to be fulfilled, viz., the same cars have to run on three-phase and direct-current lines. Probably the motors are equipped with three slip-rings and a commutator on the same rotor shaft, both being connected to the same armature winding; the three-phase voltage is reduced to the corresponding value by transformers and fed to the slip-rings, the stator serving as field for the direct-current service and as induced secondary for the three-phase work. For both services the same liquid starter may be used. The stator winding should preferably be two-phase.

The Oerlikon Company has published data on a single-phase series motor of 200 horse-power, 650 r. p. m., 15 periods and 250 volts. It has eight projecting poles; between them eight smaller commutating poles excited by the main current are arranged, neutralizing the cross-field and the reactance voltage. High iron inductions and equalizers for the multiple armature winding are used. The motor may just as well be worked by direct current.

Discussion.

Chairman Duncan: General discussion on the subject of the foregoing papers is now open.

Mr. E. Kilburn Scott: The advocacy of single-phase as opposed to three-phase systems always strikes me in this way — if you ask a man to build an engine with a uniform turning movement, he will supply you with a three-crank engine, and if you use only one of the cylinders, that is, only one line of parts, you will be considered more or less incompetent. Now, every three-phase generator, and every induction motor is analogous to the three-crank engine, and if used single-phase only, it is roughly equivalent to using the single crank.

One point which strikes me as being very favorable to three-phase, is that if you have the transformers connected in delta, and one of them breaks down, the other two carry the load. On the other hand, in a single-phase transmission and distribution, for whatever purpose, if the transformer breaks down, the circuit is opened.

Regarding the question of the utilization of alternating currents for power — if single-phase is being used, the magnetic field and, therefore, the torque pulsates with each alteration, whereas with three-phase, as with direct currents, the torque and, therefore, the draw-bar pull is steady.

Assume for a moment a locomotive for a freight train and suppose a draw-bar pull of ten tons is required. In steam locomotive practice, the locomotive will weigh about five times the amount of the draw-bar pull; or, say, fifty tons. With direct-current motors as with three-phase motors, the locomotive will also weigh say fifty tons, since it has a constant torque; but with single-phase motors, because the torque is variable, it must weigh eighty-five, or perhaps one hundred tons, depending on the character of the particular motor used. I do not want to go further at this time into the alternating-current problem, as applied to traction; but the above three points, are, I think, pertinent to the discussion on Mr. Lincoln's paper.

Mr. B. G. Lamme: In dealing with the problem of single-phase railway motors with electrical engineers during the past two or three years, I have found that their opinions are based largely on such experience as they have had with other types of alternating-current motors. They apparently make no distinction between one type of alternating motor and another, and there have been a number of points brought up regarding which I find there is considerable confusion in their minds. One of these points, mentioned in Mr. Steinmetz' paper, is that of the large

air-gap permissible with the single-phase commutator-type motor. I find that a great many engineers cannot understand why a single-phase commutator-type motor can have a larger air-gap than an induction motor of the same speed and capacity, and still have a higher power factor. I have explained this point in a non-mathematical way which seemed to be satisfactory to them, and which they can check for themselves if they so desire. This explanation is as follows:

Take a polyphase motor of any of the well-known types, but preferably of the collector-ring type, for convenience. Run the machine at full speed, and note the no-load current or magnetizing current. Then open one circuit; so that the primary or field of the motor is operated on single-phase, and it will be noted that the motor takes practically the same total apparent input as before. This is, if it is a two-phase motor, for example, and one-phase is opened, the remaining phase takes twice as much current as before. Therefore, as regards total amount of magnetizing current required, it apparently makes no difference whether the induction motor is operated polyphase or single-phase.

Next, if the secondary circuit of the motor is opened, the motor still being run at full speed, it will be noted that with *all* phases connected, the magnetizing current supplied the motor remains as before; but with only one-phase on the primary, the total magnetizing current of the motor drops to one-half, while with the secondary closed, the total current was the same for either single-phase or polyphase. This indicates at once that with the secondary closed the large magnetizing current with one-phase on the primary is a direct result of the closed or short-circuited secondary, for closing the secondary winding on itself at once doubles the total magnetizing current of the single-phase primary. Any armature which has a winding not short-circuited on itself will, when placed in this primary, have the same effect as the open secondary in the above illustration. An armature or secondary element, with a direct-current type of winding, has the same effect as the open secondary, as such a winding is not closed or short-circuited on itself in the sense that an induction-motor secondary winding is closed on itself. Therefore, it follows that a single-phase motor with a secondary or armature with a direct-current type of winding will absorb only one-half as much magnetizing current in its primary or field, as would be taken by a single-phase motor or polyphase motor of the induction type. It is, therefore, evident as the magnetizing current is only one-half of that of the corresponding induction motor, the air-gap can be very much increased if the commutator-type motor is allowed to take the same magnetizing current as the induction type.

A second point which I have found required considerable explanation is the fact that the series type of single-phase motor can give a very large starting torque with a poor power-factor. Experience of electrical engineers has been founded on induction-motor practice, in which a low power-factor at start means, in general, rather poor starting torque. They consequently believe that poor power-factors and poor torque at start go together. They do not comprehend that there is one great difference between the series type of single-phase motor and the induction motor, single-phase and polyphase, and that is that in the series type of motor,

the current taken by the motor represents torque without regard to the power-factor. That is, the magnetizing and other wattless components of the current represent starting torque just as well as the energy component. In the induction motor on the other hand, the magnetizing and other wattless components of the current supplied to the motor represent no torque, and it is only the energy component of the current that can represent torque. Therefore, if the induction motor has a low power-factor at start, it means a low energy component, and, therefore, of the total current supplied but a small proportion represents torque. High torque in the induction motor at start must be obtained by high losses, represented by resistance losses in the secondary or armature circuit of the motor. On the other hand as mentioned above, in the series type of single-phase motor, high torque at start does not mean high losses, as the wattless component assists in developing torque. Therefore, for railway work where induction-type motors are used, rheostatic control is always used in order to obtain high energy loss at start for obtaining the necessary high starting torque, but with single-phase railway motors of the series type, it is only necessary to get the required current through the motor for the desired torque, as in the direct-current series motor, and the voltage at the terminals of the motor can be adjusted to that required to send the necessary current through the motor. Full-load current through the motor will give full-load torque, without regard to the voltage supplied, and if this full load current can be supplied to the motor at much lower than full-load voltage, then full-load torque will be obtained in such motors with much less than full-load input. If half full-load voltage, for example, is required to send full-load current through the motor at start, then full-load torque will be obtained with one-half the normal input of the motor, and furthermore this reduced input will be at a relatively low power-factor. This lower power-factor at start would have considerable effect on the transmission system, but it is compensated for by the reduced input at start.

In Mr. Steinmetz' paper, where he gives comparisons of the different types of commutator motors, he refers to them as the plain series, the directly compensated, and the induced compensated. My experience has been almost entirely with the directly compensated, and that is practically the only method that the company which I represent has been using. Before the American Institute last winter, in a discussion on this subject, I referred to this type under a different term. I spoke of it as a " straight series motor ", describing it as one with all the windings in series. That was intended to distinguish it from the motor with the compensating winding short-circuited on itself. My experience has shown that such a winding is not the equal of the type where the neutralizing or balancing winding is in series with the other windings. I have also found that the best results on the average are obtained with the neutralizing winding just balancing the armature winding, not over or under compensated, and one measure for testing our compensating windings has been to put a short-circuiting connection across the terminals of the neutralizing winding. When this winding is properly proportioned, but very little current will be obtained through the short-circuiting wire.

Dr. C. P. Steinmetz: In regard to the question raised of the relative advantages of single-phase and polyphase motors,—the induction type of motor — the single-phase motor tends to synchronize much more strongly than the polyphase motor. That is, the range of efficient operation in the single-phase motor is much more limited, and by deviating from synchronous speed, the torque and power fall off very much more rapidly in the single-phase induction motor then in the polyphase motor; so that while a polyphase induction motor could still be used for railroad work, where rapid and frequent acceleration is not demanded, the single-phase induction motor is out of the question for this work, except by methods as Mr. Arnold has shown us here so nicely, whereby the motor is really not required to start and accelerate with the train. The reverse condition, however, is found with the commutator motor. Investigation of all the very many different forms of alternating commutator motors has shown me that the tendency of the single-phase commutator motor to cover efficiently a very wide range of speed is much more marked than in the polyphase commutator motor. This can well be understood. In any motor the torque is produced by the action of a magnetic field on the resultant current flowing in the rotor in quadrature position to the magnetic field. In the polyphase motor, where you have a stator polyphase field, the magnetic flux in the direction of the effective field is necessarily determined by the impressed e.m.f. and so limited. In the single-phase commutator motor, however, there is a direction in quadrature to the magnetomotive force of the impressed primary circuit, where no limit exists to the magnetic flux, except magnetic saturation, and in this direction a magnetic field can be produced which is not limited by the impressed e.m.f., but varies more or less in inverse proportion to the speed; so that such a single-phase commutator motor can be made to give the characteristic of the direct-current series motor; that is, to give a torque proportional approximately to the square of the current, while in the polyphase motor the tendency is always in the direction of a torque only proportional to the current. Going down, then, to low speeds and starting, you find that, other things being equal, the single-phase commutator motor gives the better torque efficiency as compared with the polyphase commutator motor, while the reverse is the case with the induction motor.

As regards the comparison with the single-cylinder and multiple-cylinder steam engine, after all the single-cylinder steam engine when running is not inferior in this respect to the three-cylinder steam engine, and, in fact, even now-a-days, there are steam engines built and operated at the highest efficiency which are, as far as this feature is concerned, single-cylinder engines; that is, where the multiple expansion is carried out in several cylinders connected in tandem, where, therefore, you get the pulsating torque. The objection to the single-cylinder characteristic is that the frequency of impulses varies with the speed, and is very low at low speed and results in a dead point at stand-still. But this is not the case in a single-phase motor, where the frequency of impulses is constant, is the impressed frequency of alternations, and not the frequency of speed, as with the steam engine, and is so high that the motor cannot be built with

as low momentum, as low mass, to give a noticeable variation of speed, due to the successive impulses of torque.

As regards the system of distribution, whether polyphase, three-phase or single-phase, for electric railroading,— for general distribution, polyphase systems are used almost exclusively in this country. That is, for many years we have been impressed and educated to consider this as the proper thing. I understand it is not quite so abroad Single-phase systems are still used there to a considerable extent. The polyphase system has a decided advantage in stationary motor work: the polyphase stationary motor, of the induction or synchronous type, is decidedly superior to the single-phase motor, and will remain so, and that is the foremost value and importance of the polyphase system. The polyphase generator is a little smaller, a little more efficient than the single-phase generator. I do not believe, however, that the difference in generators is so essential as to throw the balance in favor of the polyphase system. But it is in the motor work. In every other respect the single-phase system is simpler and more reliable, and even if the three-phase system by the use of three transformers connected in delta gives the result that if any one of the transformers burns out, the other two can maintain the service: in the single-phase system by using two transformers, which means larger units, and a better arrangement, if one burns out, the other one can maintain the service, so you still have an advantage.

Mr. E. Kilburn Scott: It has to be switched in.

Dr. Steinmetz: Switching, controlling, everything is simpler, and more convenient, in the single-phase system than in the polyphase system, and my opinion is that if it were not for the question of motors, the polyphase system would never have reached its present standing.

Now, when you come to railway work, and the commutator motor, this question changes, and the advantage of the polyphase system becomes a disadvantage. The motor must be a single-phase motor, and you must run a single-phase system from a polyphase generating system. Now we can indeed do that by distributing the railway load on the different phases, operating a two-track road from a two-phase system by having one track on one-phase and the other track on the other phase, or cutting the road up into sections and connecting the sections with the different phases. In railroading, the foremost condition is absolute reliability regardless of everything else. Now, as soon as you cut up the system in different phases, where two tracks are in different phases, any switch or transfer device from track to track leads to difficulties. If you cut the road up into sections, you must have a dead section between the two longer than the longest train that ever will be run, otherwise you are liable to run the same train on the two different phases, getting a dead short-circuit. I think it is objectionable to have any possibility of a place on the road where a train may get stalled and be unable to proceed, and I think these objections may lead us again to consider the single-phase generator, and I believe if the single-phase generator is taken up with the modern engineering methods, with modern experience in design, we can get a single-phase generator which, while probably not

exactly as small and efficient as the three-phase, will nevertheless be so close to it, that it will fully fill the requirements, and my personal opinion is that if you run railroads with single-phase motors, if there are no other conditions to be met, the best way would be to generate your power single-phase and transmit it single-phase and operate the whole system on the same circuit with the greatest possible simplicity, doing away as far as possible with the duplicating of transformers, the duplicating of feeders, the existence of dead sections and the inconvenience in switching or transfer.

Mr. A. H. Armstrong: The adoption of either three-phase or the single-phase generators is not a purely engineering question, but it is necessary to consider the commercial aspects of the case as well. There are probably operating in this country some half million kw of rotary converter and three-phase generating apparatus. The object of developing the single-phase railway motor along the lines of 25-cycle supply was that it might utilize so far as possible this half-million kw of apparatus. In advocating, therefore, the single-phase generating and distributing system, we are confronted with the possibility, in many cases even the necessity, of using the supply of power already available. To meet this condition, the company which I represent has devised a scheme of balancing by the three-phase-two-phase step-down transformer connection, making each sub-station balanced in itself, and equally loading the three legs of the usual three-phase distributing system. By this means it is possible to use existing distributing systems, and to consider the claims of stationary motor work in any new system that is considered. The single-phase system of generation and distribution is of course the simplest possible for railway work. It approaches more nearly to the direct-current system of distribution, and is preferable, but many electric railway installations have reached such magnitude, and have so many secondary claims upon them, such as lighting and general power distribution, that the railway interests alone cannot be considered by themselves. Three-phase generating and distributing systems already exist, and must be utilized, and secondary claims will probably influence the introduction of the same class of machinery in the new plants. Thus, while the single-phase system is preferable and simple, considered from the engineering standpoint alone, it is probable that three-phase distribution, or multiphase distribution, will have to be carefully considered even though the motors adopted are of the single-phase type.

Mr. E. Kilburn Scott: Mr. Steinmetz, will you tell me where this analogy is wrong? Suppose I go to a carpenter and ask him to make me something to stand upon which shall have the *minimum quantity* of material and the *maximum strength*, he makes me a *three*-legged stool. If he should make it with four legs, which is analogous to two-phase,—well, it might stand on four, but the chances are it will rest on three only, the extra leg in other words being so much wasted work and material. If he should make it with two legs, which I think is analogous to single-phase, it would be in unstable equilibrium.

Mr. Steinmetz: But if you make a vehicle with three wheels, a tricycle, you can never get the speed out of it that you can out of a bicycle.

That is, as soon as you get motion and have dynamic conditions things change entirely from static conditions.

Mr. Scott: Yes, I see.

Chairman Duncan: We should like to have some further discussion. There are certainly gentlemen present who can add to our information on the subject. Mr. Leonard, we should like to hear something about Mr. Arnold's locomotive. I know you have considered that type.

Mr. H. Ward Leonard: I believe, Mr. Chairman, that I was the first to urge the idea that single-phase, high-tension generation and distribution were essential for heavy railway work, and as some of the gentlemen present may not understand the system that I proposed, since it was many years ago, I will state briefly that what I proposed was a high-tension single-phase system with a single-phase motor upon the locomotive running at a constant speed, and driving upon the locomotive a generator, which generator would have a separately excited field, by means of which the voltage of the continuous current in the secondary could be varied as desired and reversed, by which means we could secure in the armatures of the propelling motors of the locomotive any desired voltage to accelerate from rest to full speed, with a minimum consumption of watts and with the many advantages of perfect speed control, restoration of energy, etc. Mr. Arnold's proposition follows similar lines, to the point where the shaft of the single-phase motor is reached. From that point he uses compressed air in conjunction with the torque of the single-phase motor, and he secures very many beautiful features and important ones, although, as I believe, at the expense of simplicity. He has one advantage which may have considerable weight, although I believe that it will not be so influential as to be of very great effect, and that is the storage of power for the operation of the train without electric current for a short distance. But a system having reciprocating parts and the complexity due to the necessity of a good many valves and automatic devices, I personally do not think is likely to compare in reliability of service with a single revolving part without separate automatic devices or reciprocating parts. A point in connection with my system which is also likely to be important, perhaps, is that although a high-tension current would preferably be led upon the locomotive, it is led to a single-phase motor which is an entirely separate device and can be entirely insulated at the shaft from the rest of the locomotive, so that we reduce to a minimum the liability of the high-tension energy reaching any portion of the locomotive which has to be handled, or where a person might be exposed to it.

As to the comparative weights and first cost, it is difficult to form a conclusion with any of the data that we have at present at hand as between the air-storage scheme and the transformation at variable voltage, but I should be inclined to expect that the first cost and weight for my system would be rather less than for the other. In that connection I was interested to notice the figures which are given in Prof. Niethammer's paper, on page 237, where Table VIII. gives the weights for the direct-current, three-phase and single-phase apparatus. Considering the three-phase and the single-phase, and putting those figures into the weight per horse-power of the electrical equipment on the locomotive, and putting

the kilograms roughly into pounds, we get the following figures: Three-phase, Brown-Boveri, 72 lbs. per h.p.; Siemens & Halske, three-phase, 89 lbs.; A. E. G., three-phase, 53 lbs.; Ganz & Co., three-phase, 60 lbs. Single-phase.— Finzi, 88 lbs.; Union, 73 lbs.; Oerlikon, 60 lbs. This matter of weight is oftentimes an important one, and while considering the weight of transforming apparatus such as Mr. Arnold proposes, and such as I propose, I wish to call attention to the fact that we must not lose sight of the consideration that for the same maximum operating torque with satisfactory commutation the weight of motors on my system will be very materially less than is likely to be realized even after the highest perfection of the single-phase type, and that, therefore, there is quite a little margin of weight at that point available to compensate for the weight of the motor generator. Furthermore, I consider that if my system has any virtue, it lies principally in the direction of the production of a very large amount of power upon a locomotive and the possibility of controlling by very simple means a multiple of very heavy locomotives, where questions of simple, uniform acceleration with a minimum of energy, simplicity and reliability of control and the restoration of energy are considerations that will be very important.

When considering heavy locomotives I think there will be a very great advantage to be found in a system such as mine, which employs motors in which the field of the motor is entirely independent of the armature current. What I mean by that is this,— a heavy locomotive will be worked, and must be worked, to the limit of its maximum tractive effort, and every artifice must be employed to secure the maximum tractive effort from the locomotive,— the same is true, of course, of the steam locomotive, — and the result is the parallel rods of the steam locomotive, which are probably the chief curse of the steam locomotive to-day. They are a necessity in order to secure the maximum tractive effort with a certain weight on drivers. With series motors we will also need parallel rods. If we attempt to leave the parallel rods off it will be evident that with perhaps six or eight drivers on a side, representing six or eight different motors, some one of those, if we push the motors to the limit, will skid before the rest, and when it does so skid we have a condition which is comparable to the skidding of a steam locomotive by too rapid opening of the throttle, and it becomes necessary to stop, go back to the starting condition and try it again. Now, that is due to the fact that a series motor has a speed which is dependent upon its torque, a speed which is dependent upon the current, but if you have a motor with a separately excited field and in which the counter volts balance the impressed volts without any rheostat in that circuit, it is, as you will see, impossible for any racing away of the motor in case any particular motor does tend to skid; which means that with such a system as I suggest we can operate in multiple a number of different motors and secure the effects of an invisible parallel rod, without the mechanical complications and handicaps which that imposes on account of the rigid wheel-base and the consequent difficulties upon the curves. Therefore, I think that the question of heavy locomotive practice will lead strongly in the direction of a separately excited field or some other artifice, which may of course come.

which will enable us to secure the effects of the parallel rod electrically, without the mechanical difficulties.

Mr. W. L. WATERS: Referring to Mr. Bragstad's paper, or rather to the remark in that paper to which Mr. Steinmetz called attention — that analytical methods are necessary for dealing with problems such as we have in the single-phase motor, and that graphical methods are of little use, it has always seemed to me that it is more a question of a natural trend of a man's mind than that any arbitrary dogmatic statement can be made, either that the analytical or that the graphical method is the only one to use. Speaking from a personal point of view, I have always had to adopt analytical methods to obtain a complete and comprehensive understanding of the problem in the first place, but as soon as it comes to practical designing, I find it necessary to adopt graphical methods and rough approximate rules obtained from experiments. I think that one thing students have always to learn before they can become practical engineers is that designing is not a question of solving differential equations dealing in complex functions and imaginaries, but one of deducing rough rules from experiment, and from previous experience with similar types of machines. As it has been very aptly put — designing is an art, rather than an exact science.

Coming to Mr. Lincoln's paper, I think that Mr. Lincoln hits the nail on the head, when he states that directly you talk about potential to earth, instead of potential between conductors, the single-phase system is on a par with the three-phase. We have got so used to talking about three-phase transmission that we have almost come to believe that no other system of transmission is possible. The original three-phase transmission work, and most of the three-phase distribution work at the present time, has been done with three-phase cables, in which, of course, the potential between conductors decides the strain on the insulation. But, as Mr. Lincoln points out, when we come to modern overhead transmission lines, it is the potential to earth that decides the strain on the insulation, and this being the case the single-phase system is, for overhead work, equal to the three-phase. It seems peculiar that after ten years or so of almost exclusive use of three-phase system, that we now seem likely to return to the original single-phase system, which has been continually advocated by Ferranti and which was used in the first commercial transmission — the 10,000-volt Deptford-London line.

The main disadvantages of the single-phase system are, of course, obvious. That with a single-phase alternator you do not get the full output that the machine is capable of giving, and that the single-phase commutator motor is a much more complicated machine and much more liable to break down than the three-phase induction motor. These disadvantages, however, are not sufficiently serious to prevent the single-phase system from having a wide application.

Dr. STEINMETZ: When considering the development of a new field in engineering, we first consider what appears to be the simplest and the best arrangement, and endeavor to introduce that. However, in every case we also must consider the existing state of the art, what has been before and what is there. If a cataclysm to-morrow should wipe out all our civiliza-

tion except the human intelligence and we should then proceed unfettered by existing things to reconstruct it, we would do very many things differently than we are obliged to do now. One of these features my friend Mr. Armstrong has referred to. While single-phase generation and transmission would be the simplest, the enormous magnitude of existing three-phase plants may lead us to utilize, in generation at least, polyphase systems. It may or it may not. The future alone can show that. There are a number of features with regard to the use of commutator motors in railway work which are of similar character. At least in this country there are very few villages even which do not have a direct-current railway system. After all, the electrification of the steam railway has not made such progress as enthusiasts believed it would ten years ago. Electric locomotives have been introduced and are being introduced, but in most cases you find special requirements, either an underground tunnel or something of similar character. But what has taken place is the exact counterpart of what took place three-quarters of a century ago. The early attempts of the steam locomotive to replace the horse in front of the stage coach were not successful, but a new motive power required new arrangements, and the steam locomotive and the railroad train has been developed. The horse has not disappeared but has been relegated to another field. You see the same taking place now in electric railroading. You do not see in general, at least not yet, the electric motor replacing the steam locomotive, but you see the trolley car paralleling the steam railroad and either taking away a certain class of traffic for which it is much more suited, or developing a traffic of its own. The feature whereby the trolley car, in spite of its usually lower average schedule speed, beats the steam railway train, is the absence of terminal stations and the absence of a time-table. With the steam railroad train you have to go to the depot, and you have to consult beforehand a time-table.

With the interurban electric railway you pick up the car anywhere in the city, either the interurban car directly or a transfer car, and you do not look for a time-table but wait for the next car which comes along in a few minutes. That is, I believe, the main advantage of electric railroading. But as soon as you introduce a motor which is specific for interurban service, for long-distance travel, which cannot run over your city systems, you give up that advantage and you are only on a par with the steam railroad train. Even then we still have great advantages in the rapidity of acceleration, the greater schedule speed we could secure with the same maximum speed, absence of smoke, etc. But all those appear to me minor advantages compared with the advantage of not requiring terminal station and time-table. With the alternating motor, this means adapting the new systems to what exists at the present day. You have to limit the choice of your motor to such types as can be easily applied to both characters of service. Hence, to retain the main advantages of electric railroading, you require a motor that will run equally well on the alternating, long-distance trolley circuit, as on the direct-current city distribution. That is one of the features on which you have to compromise. It means that you must carry the same car, the same motor, with equal efficiency of operation, of acceleration, over the 500-volt city system and over the

high-voltage long-distance line. This feature, and this class of service, determines, to a certain extent, the type of motor and gives the preference to the compensated motor or Eickemeyer motor over the repulsion motor, although in its speed-torque characteristics some advantages exist in the latter. For other classes of service, as, for instance, heavy freight service on trunk lines, possibly other types of motors may be preferable. We must consider that at present, after the development of nearly a quarter of a century, one type of motor has been brought forward and everything else dropped to practical oblivion, and that is the direct-current series motor, as most perfectly fulfilling all the requirements of electric railroading as it is at present. This does not mean, however, that it will remain so. For many years all the requirements of alternating motors have been fulfilled by the polyphase induction motor, and still we now demand a single-phase commutator motor. You see, there may be fields which are not touched at present, but which will have to be taken up by the electrical engineer in railroading, and for which a different type of motor may be preferable. All the classes of electric railway service at present, whether it is the city tram car or the rapid transit road, elevated or subway, or the suburban or interurban service, are very similar in their characteristics. They all require a motor which is able to give a very high torque, that is, a very rapid acceleration, sustained up to a considerable speed, and beyond this speed, at the end of the high acceleration, a torque curve which decreases very rapidly but still extends to considerably higher speeds, running down to 20 per cent or less of the torque of acceleration at twice the speed which is reached by full acceleration torque. In addition thereto you require means to operate efficiently at moderate torque and low speeds, which is fulfilled by the series-parallel connection. In city tram car work you have to stop very frequently, at very irregular intervals. Therefore you have to be able to accelerate very rapidly, with heavy acceleration, so as to maintain good schedule speed. You must have rapid acceleration up to considerable speed and then get the benefit of favorable conditions of road by running up to high speed with decreasing torque. The torque must decrease rapidly at high speeds, because otherwise on a level stretch you would either have to cut in and cut out continuously or you would run to such speeds as were beyond your motor capacity. Furthermore, in districts of heavy traffic you have to run slowly. This means series-parallel control. When you come to suburban or interurban service, you have the same characteristic except that the speeds are higher, and the stops less frequent. In rapid transit, you have again the same characteristic, only larger motors and higher speeds. Now, the induction motor gives you also a sustained acceleration but a torque which drops down to zero immediately above the speed reached with full acceleration torque. That is that part of the speed curve from the end of maximum acceleration to the speed of free running (about twice the former speed), or the acceleration on the motor curve, does not exist with the induction motor. Acceleration on the motor curve, however, is the most efficient acceleration. You cannot go beyond synchronous speed and so cannot get the benefit of the track, with the induction motor. Now, you can indeed extend your curve by making synchronism the free running speed. But that means that you

have half the rate of acceleration, assuming the same size of motor, or if you desire the same high acceleration, you require twice as large a motor, which obviously is not feasible, because usually you have not the space. Hence, where you have to accelerate rapidly to high speeds, where you have to get the benefit of favorable conditions of the road, the polyphase induction motor is not successful. Under favorable conditions, for instance for the class of work where the acceleration curve does not differ much from the running curve, as on heavy grades, on mountain railways, as mining locomotives, where indeed the character of the work is not railway work but rather elevator work, there the three-phase motor is successful, and there are mountain railways in existence in this country, as well as abroad,— with three-phase induction motors. But that is not regular railway service. The different alternating-current commutator motors give a torque curve very similar to that of the direct-current series motor, except that the torque decreases slightly less with the increase of speed, the torque curve as function of the speed is less steep (the induction motor as stated gives practically a vertical line). The repulsion motor, as stated in my paper, gives the steepest curve; the plain series motor, without compensation, the flattest curve. The result hereof is that with the same speed of free running, the alternating-current commutator motor, with the same acceleration torque, will not sustain the acceleration up to quite the same high speed as the direct-current motor, but will strike the motor curve at a lower speed. This gives a higher efficiency of acceleration, but with the same maximum acceleration, the average acceleration will be less, and so, to get up to the same speed, it will take a slightly longer time with the alternating-commutator motor than with the direct-current series motor, but the acceleration will be more efficient; because the larger part of the acceleration is on the motor curve. Where you are able to increase the maximum acceleration you can get the same average acceleration with the alternating-current motor as with the direct-current series motor, and that at higher efficiency, other things being equal, in the alternating motor, but you have to go to higher maximum values of acceleration. Hence where you are limited by the comfort of the passengers you cannot do that, and, therefore, for some classes of service, where you have to accelerate at the maximum value permitted by the comfort of the passenger, the direct-current series motor gives you a more rapid average acceleration than the ordinary alternating commutator motor. This, however, does not preclude the alternating-current commutator motor being modified so as to give the same characteristic as the direct-current series motor and that is being done. But the motor as it is in service at present gives a torque curve of slightly less steepness than the average direct-current series motor. The counterpart of this lesser steepness of the torque curve of the alternating-commutator motor is that you can run over a wider range of speed with the same resistance, or the same potential.

Mr. Lamme: Several points have been brought up since I spoke last, in connection with the fact that we have had to adapt this single-phase railway system to existing conditions. It has been mentioned that single-phase would be preferable to polyphase, both for generation and transmission, but that the system has to be adapted to existing generating plants

and that the nearest approach we could make to the ideal system would be to transmit at three-phase from existing stations, transform to two-phase, and feed each of the two phases to the trolley as independent single-phase lines. In connection with the use of single-phase throughout, it may be of interest to go back to the first paper on single-phase railway motors of the commutator type which was presented two years ago this month, before the American Institute. In that paper I called attention to the fact that the Westinghouse Company had taken a contract for a single-phase railway using commutator type motors. Among the various features of the system as described, it should be noted that our proposition was for single-phase throughout, the generators being wound for single-phase 15,000 volts, and feeding directly into the transmission circuit. Step-down transformers were to be used in the sub-stations, or transforming stations, and single-phase current was fed to the trolley circuit and to the motors. That was considered an ideal system, and such an arrangement could be adopted in this particular case because the road was a new one throughout, and was not limited to any extent by existing conditions. But most of the projects which have been brought up since that time have been in connection with existing power-plants, or are roads which expect at some future time to tie up with other plants, so we have been obliged to accept the polyphase generating and transmission plants with the single-phase distribution beyond the power-house, or the transforming stations. Take for example a single-phase road which is now being installed between Cincinnati and Indianapolis. The company installing this had already bought machinery for a three-phase generating plant with direct-current distribution from converters. They changed over to the single-phase system after the machinery was partly completed. It was suggested that a straight single-phase plant throughout would present many advantages, but the customer could not see his way clear to make the change so late in the day. Therefore the customer decided to stick to the three-phase generating and transmitting plant with transformation to two-phase in the sub-stations. The line is divided, one branch being fed from one phase, and the other branch from the other phase. We have found that similar conditions hold true in many other plants. Another condition which came up in some of the earlier projects was that the customers were somewhat doubtful of the single-phase system on account of its novelty, and they took the stand that if they put in three-phase generation and transmission, they would always be in position to adopt rotary converters afterward, if they found it desirable to do so. We have heard but little on this point in the past year or two.

Mr. E. Kilburn Scott: How do you change the three-phase into single-phase on the line you speak of?

Mr. Lamme: Consider one branch of the line in one direction from the power-house as one phase, and the other branch in the opposite direction as the other phase.

Mr. Scott: Can you transform from three-phase to single-phase with transformers? Can it be done like the three-phase two-phase arrangement?

Mr. Lamme: Well, that I am not prepared to say. Another feature

worth considering in the Baltimore-Annapolis road was the frequency adopted. At that time we proposed a frequency of about two-thirds of what is used at present. That frequency was then considered as the most suitable one taking everything into consideration, as it was better for the motors, transmission line, and for the generators. I still hold to the opinion that for the motors a low frequency is better than a higher frequency, especially for larger capacities of motors, and I think that as we take up heavy locomotive work that this question of a frequency lower than twenty-five cycles will be found of great importance. It is entirely possible than when the steam roads are electrified it will be found advisable to adopt some frequency other than twenty-five cycles. In a great many cases the power-plant requirements for the heavy railroads will be so great compared with existing plants that these systems can adopt their own frequency. It was found that in pushing the lower frequency, it was much the same as in pushing the single-phase. We could not get people to adopt it, largely on account of utilization of existing plants. We found that was the greatest objection to low frequency. We found that even in the case of heavy railroads, with plants of four or five times the capacity of all the other plants in the same district, they nevertheless wished to start out with a frequency which corresponds with that of the smaller plants in the same neighborhood. I think they will pull away from that policy some day.

Another point brought out in the Institute paper referred to was that the type of alternating-current motor to be used was perfectly adapted for operation on direct-current, as it was primarily a high class direct-current machine. It was stated that the complication necessary for operating on both alternating and direct currents was much greater than for either the alternating or direct current alone; because it was necessary to have rather complicated switching devices for throwing from one system to the other, if the combination system was used. At that time it was thought that such an arrangement would be entirely too complicated, and that railway engineers could not possibly accept it; yet within a comparatively short time after the publication of that paper, we found engineers who were willing to consider it, and within the past year contracts have been closed with roads which are to be operated on alternating current on suburban and interurban service and direct current on the city service, and the extra complication of such a system does not seem to be prohibitive to them. The series-parallel connection of motors was considered for this service. We found that on many of the projects there was no particular advantage with such an arrangement. In one large road which we are installing, the service across country will be at a very high speed, and it was found that to get the necessary low speed in the direct-current city lines it was necessary to connect all four motors in series. Therefore, there was no advantage in operating series-parallel on the direct-current part of the road as only the series combination could be used. We, therefore, adopted the combination with four motors in series for the direct-current and four motors in parallel for the alternating service, and speed variation on the alternating service is obtained by means of a number of loops or taps on the lowering transformers. In this way we obtain on the alternating-current service

better conditions than could be obtained with series-parallel, as we have more than two efficient running steps and the starting conditions are also better. I think that where the speed on suburban service is comparatively low, it might be possible to use the series-parallel arrangement of motors, with the motors thrown in series on the city service on direct current, but we have found in general that in going into the cities, or through towns which are not of large size, in many cases a similar arrangement has been to put up an extra trolley wire alongside the direct-current trolley wire, this extra wire being supplied with alternating current at about 500 volts. By placing one of the transforming stations near the junction of the suburban and the city service, we can feed the 500-volt city trolley wire from a low voltage tap on the lowering transformer. In this way we can have low-voltage and high-voltage trolleys supplied from the same transforming station. On the lowering transformer on the car itself, we have also a low-voltage tap corresponding to the voltage on the city trolley. When the car is to be changed from the high-voltage trolley to the low-voltage, the circuit is switched over to the low tap on the car transformer and the same control apparatus is used as for the suburban high-voltage service. That has proved to be a very simple arrangement, and it has been adopted on most of the roads which we have sold. About seven or eight roads have been sold which utilize such an arrangement, and very few have so far found necessity for the extra complication which will be required for operation of both alternating and direct currents.

In the preceding discussions, there seems to have been no particular comment on the question of the most suitable frequency. Twenty-five cycles seems to be the most suitable frequency at the present time for commercial work, simply because existing plants have been installed with this frequency. It is possible to go to somewhat higher frequencies successfully with a somewhat larger motor, but with corresponding poorer performance. Better results can be obtained from the motor at lower than twenty-five cycles, but such lower frequency will possibly not be adopted extensively until we get into heavy railroad work. But if we should adopt lower frequency, and thus break loose from existing systems, then will be the time when we can also adopt the straight single-phase system.

Mr. A. H. Armstrong: Mr. Chairman, the product of the engineer is at the best a compromise. With the rest of us, Mr. Lamme has gone through the battle of frequencies, starting at 125 and 130 cycles per second with a gradual reduction to 25 cycles, until we thought the bottom had been struck, but there are certain advantages which perhaps warrant the introduction of 16 2/3 cycles, or even lower. I believe 15 cycles is already in operation on the other side of the water.

Closely allied to the confusion of frequencies, is the babel of voltages. Contrasted with the two accepted standard frequencies of twenty-five and sixty cycles, there are the multitude of standard voltages with their modifications. Voltages are at the best mixed up, and no new distributing system can go in unless it takes account of the voltages existing in neighboring plants with which it may be consolidated at some future theoretical date, a possibility always kept fully in mind by the promoters of the new

installation. But in adopting alternating-current motors for railway work, we have an open field so far as trolley voltages are concerned, and I am glad to see that there is a fairly uniform movement toward adopting 2200 and 3300 volts as the two standards. I do not quite see how we can adopt one of these in preference to the other, but it seems necessary perhaps to adopt both of them for the present, and by a gradual course of elimination to settle on one as being the best fitted for general work.

As regards the fitness of the alternating-current motor for railway work or its proper field of action, very little has been said this morning beyond Mr. Steinmetz' remarks, and I would like to supplement them by two or three observations of my own. I have been fortunate in having an insight into the probable plans of a steam-operated road which is going to change over part of its service to electrical operation. The engineers in charge of the work are very progressive, and seem to consider nothing but the alternating-current motor as available.

Another thing that strikes me as instructive is the fact that although they have their own private right of way, their own terminal stations and are entirely isolated from any influences of direct-current city work, they will consider nothing but the operation of alternating-current motors on direct-current circuits. The road is being electrically equipped to take care of the suburban passenger traffic, the changing over of locomotives for handling freight traffic not yet being contemplated. They realize fully that their receipts have been eaten into very heavily by the inroads of parallel electric lines, all of which have the right of way over city streets. The success of these roads is due largely to the fact that they can pick up and discharge passengers on city streets, and the steam road management do not consider it feasible to give up one of the most valuable assets now enjoyed by the electric roads. In operating their system electrically, therefore, they are considering the giving up either in whole or part of their terminal stations and the operation of their cars on their own private right of way between cities and over the city streets at the terminals, in fact duplicating almost exactly the present operation of our city and suburban systems.

Mr. Lamme made a remark about the advisability of installing a separate alternating-current trolley system in small towns en route, although they may have a present tramway system operated by direct current. It seems to me that the trend of progress in alternating-current motor work necessitates that these motors must operate over city systems with direct current. I have a case in mind where a road was to be operated on the suburban sections, some thirty or forty miles, with alternating current, connecting two city systems at the termini. The expense and complication of introducing a separate alternating-current trolley in the cities was very great, the expense not being so much of a consideration as the complications of equipping every street in the city leading to the car barns, and in fact any route liable to be taken by the suburban cars.

In adopting an alternating-current motor system that is applicable to general work, the first consideration is of course to have it operative; the second is to simplify the character of the mechanism and controlling ap-

paratus as much as possible. If a motor control is adopted that will be operative on both alternating-current and direct-current circuits, it may or may not necessitate giving up the advantages of potential control. Simplification would call for plain rheostatic control similar to that employed now in the operation of direct-current motors. In fact, motors are in commercial operation using plain rheostatic series-parallel control both for alternating-current and direct-current circuits, the control being identical in each case, and effected by a standard direct-current controller with slight adaptation, the only change made being the cutting out of the blow-out magnet when alternating currents are used.

Mr. Steinmetz pointed out the advantage enjoyed by alternating-current motors of a more flexible speed-torque curve than that met with in the design of direct-current motors. This makes it possible to accelerate to the full rheostatic point with fewer steps, in less time and with less resistance loss than is possible with direct-current control. It furthermore simplifies greatly the control of motors when operating a combined alternating-current-direct-current system. Ordinarily, series-parallel control is not placed at such a disadvantage in regard to efficiency of acceleration compared with potential control of alternating currents. This is especially true considering the extra apparatus required, if induction-regulator control is used, or the extra complication involved if potential control is effected by taps off the main step-down transformer.

There are two general fields for alternating-current motors presenting themselves for immediate notice; the suburban field, calling for a motor capable of operating with direct current over city streets, because such roads depend upon city traffic and frequent stops for their success; and the second field is either main-line freight work, or the more immediate problem of our mountain grades. In the latter case the road is entirely isolated from any direct-current influences; it does not cater to local passenger traffic, but is used for through haulage only; there are no sentimental resources influencing the adoption of electricity, but it is installed purely from financial considerations of lower operating cost compared with steam locomotives. On this class of road it seems probable that the operation of motors on direct-current circuits will not have any influence in determining the motor to be used. The system is purely alternating throughout, operates at practically a constant output, no accelerating problems are present, and potential control is very convenient and effective for controlling motors.

Mr. Leonard brought up the point of the weight of the alternating-current equipment compared with direct current. At present, such equipments weigh approximately 25 to 30 per cent more than direct-current equipments of equal capacity. This increased weight, while it has an effect upon the first cost of the apparatus, has very little effect upon the operation of such roads as are influenced by the adoption of alternating-current motors. The alternating-current motor is essentially a suburban or high-speed motor, or else a freight motor. It is not intended for city work, not being so well adapted for this class of service as the direct-current motor with its lower internal losses in acceleration.

A car weighing thirty tons, say, with direct-current apparatus, and thirty-three or thirty-four tons with alternating apparatus, will require practically the same energy when operating at a maximum speed of forty-five or fifty miles an hour. In other words, a slight increase in the weight of the car will not greatly influence the watt-hours per ton mile required by that car when effecting a given schedule on our suburban systems. In city work, however, an increase of 10 per cent in the weight of the car calls for fully 10 per cent increase in the energy consumption, due largely to the fact that the wind friction, which is the controlling factor in high-speed service, is almost entirely eliminated at the low speed incident to city traffic, and the energy consumed by the car goes up in direct proportion to its weight. The weight of the alternating-current apparatus, therefore, cannot be brought up as an argument against its adoption in the practical work for which the alternating-current motor is primarily adapted.

Mr. H. Ward Leonard: The closing remark which Mr. Armstrong made was to the effect that for rapid acceleration work the increased weight of the alternating-current motor would be a serious handicap to it, that the increased weight of the car would require increased energy in direct proportion to that increase of weight. I should like to say in reply to that, that that remark is not broadly true, as it would not be true in the case of such systems as restore a considerable portion of the energy required for the acceleration, during the period of retardation, which, of course, is one of the points I urge most strongly in connection with my system.

Mr. P. M. Lincoln: The company which I represent have until recently recommended a trolley voltage no higher than 1100, for the reason that we believe that a voltage of such nature will not require a complete modification of the trolley line insulation. The same style of trolley insulation as is used on the present 500 volts will, we believe, be suitable when properly reinforced for a voltage of 1100 volts alternating. But on going to the higher trolley voltages which have been mentioned, viz., 2200 and 3300, we are of the opinion that the ordinary insulation as at present used on 500 volts will not answer, nor will the type of insulation answer. It will require some new type of trolley insulation. For that reason we have recommended that the trolley voltage be not increased to these higher voltages until a new type of insulation has been developed. That was at the beginning. As it stands now, however, the new types of trolley insulation have been developed, and there is no bar to the increase in trolley voltage to 2200 or 3300. The trolley voltage is bound to increase. As the requirements of the circuit increase the best and the easiest way to take care of it is by increasing the trolley voltage. It is a problem which is bound to come.

I was considerably interested in Mr. Armstrong's remarks concerning the controller for a. c. cars which has been proposed, viz., using the ordinary direct-current controller for alternating currents by simply cutting out the blow-out magnets. It seems to me that that is a step to the rear. A good many years ago when controllers were in their infancy, the blow-out magnet was not used, and in order to make a successful controller the blow-out magnet was almost an absolute necessity.

It has been my experience, as well as the experience of those with whom I have been associated, that it is considerably harder to take care of contacts which are operating with alternating current than of those which are operating with direct current. The alternating current will bite into the contact pieces, other conditions being equal, considerably more than the direct current will. Therefore, I do not see how an ordinary controller which requires a blow-out magnet for direct current is going to operate successfully when used on alternating current without any apparatus to interrupt or to cut down the deleterious effects of the spark. Possibly for small equipments such an arrangement will operate satisfactorily, but when the amount of power involved is large, as it is in the larger sizes of equipments, I do not see how such a scheme of control will operate satisfactorily.

NOTES ON EQUIPMENT OF THE WILKESBARRE & HAZELTON RAILWAY.

BY LEWIS B. STILLWELL.

The equipment of the Wilkesbarre & Hazleton Railway, which was completed in the spring of 1903, has been referred to in some detail in technical publications, but it is thought that a brief description of certain features, novel in whole or in part, particularly the covered third rail and the special form of collecting shoe employed, should be recorded in the proceedings of this Congress. The fact that this was the first railway of any considerable length in America to be equipped for commercial use with a protected third rail, and that for the last 18 months it has been in highly successful operation may make the following descriptive notes relative to construction and to performance of some value to engineers who may be called upon to deal with similar equipment problems.

The more important noteworthy features of this railway and its equipment are:

1). The use of a contact rail covered by a plank guard to protect it against snow and sleet, and to prevent accidental contact by people crossing the track or walking near it;

2). The elimination of all grade crossings;

3). The fact that it traverses a rugged and mountainous country, level stretches of roadbed being practically insignificant, while there are several stretches of 3 per cent grade not less than four miles in length;

4). The use of cars weighing 42 tons, net, without passenger load, and equipped with four motors of 125 horse-power (one hour rating) each;

5). Brake equipment so designed that no one accident to any part of the rigging can render all brakes inoperative;

6). The use of a portable converter station in the form of a car carrying transformers, converters and necessary switch gear;

7). The use of a soldered — not riveted — rail bond.

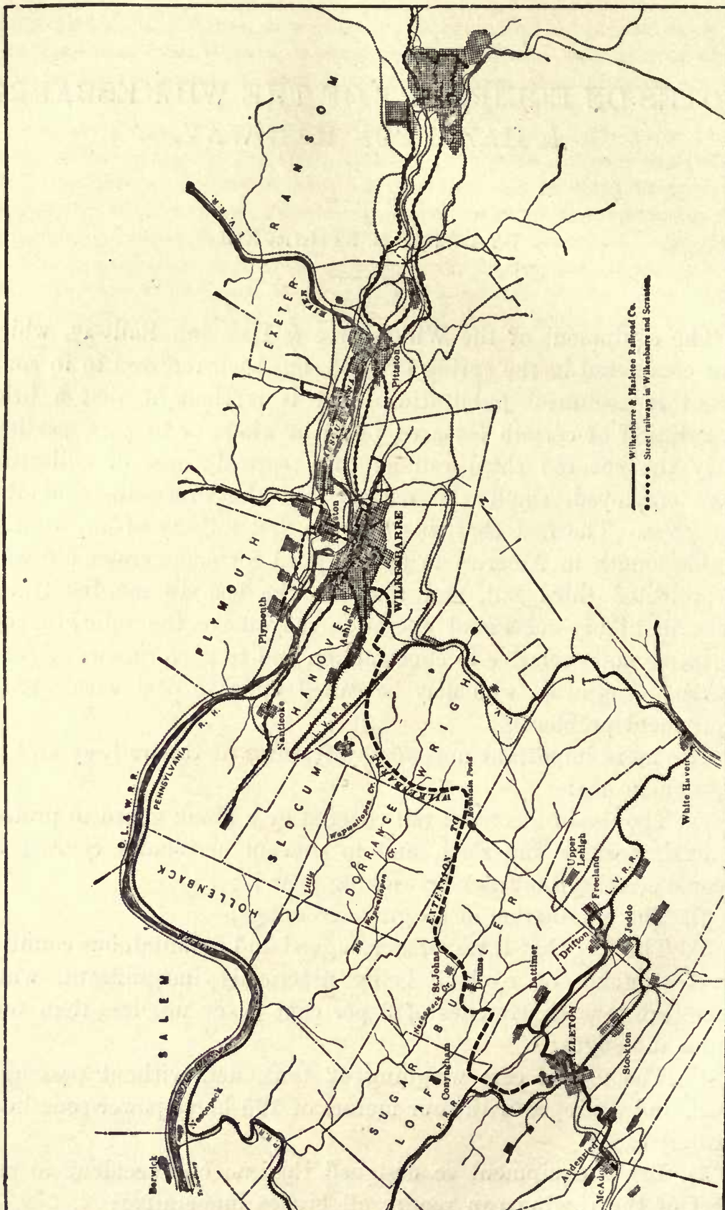

Wilkesbarre & Hazelton Railroad Co.
Street railways in Wilkesbarre and Scranton.
RANSOM
EXETER
Pittston
PLYMOUTH
Plymouth
WILKESBARRE
HANOVER
Ashley
Nanticoke
SLOCUM
DORRANCE
WRIGHT
Mountain Pond
HOLLENBACK
PENNSYLVANIA R. R.
D. L. & W. R. R.
BUTLER
St. Johns
Drums
Upper Lehigh
Freeland
Jeddo
Drifton
Stockton
White Haven
Conyngham
SUGAR LOAF
SALEM
Nescopeck
Berwick
Audenried
McAdoo

Fig. 1.

Description of Railway and Equipment.

The railway is 26.2 miles long, has a single track and connects the cities of Wilkesbarre and Hazleton in northwestern Pennsylvania. It competes with two steam railways, the Lehigh Valley and a branch of the Pennsylvania, both of which were in operation long before their electrically equipped competitor was projected. The maximum grades used by the steam railways approximate 2 per cent, and the distance between their respective terminals in the two cities is 50.4 miles in the case of the Pennsylvania and 49.6 miles in the case of the Lehigh Valley. The country between Wilkesbarre & Hazleton is mountainous, the new railway being compelled to cross not less than three ranges, as shown in profile, Fig. 2. The routes of the three competing lines are shown in the map, Fig. 1. As will be seen by reference to Fig. 2 the terminus

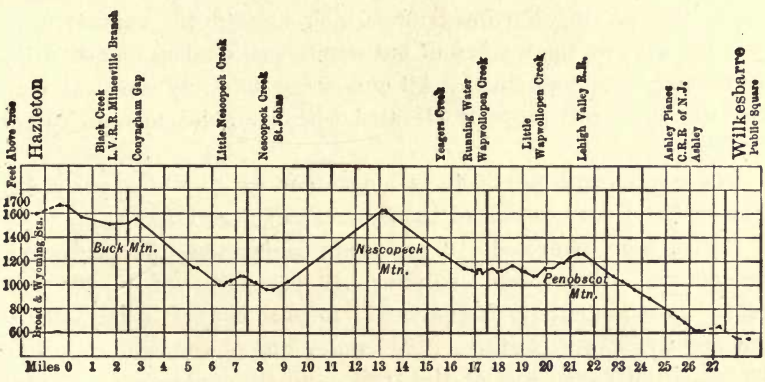


Fig. 2. — Profile of preliminary location.

of the line in Hazleton is nearly 1200 feet above the Wilkesbarre terminus. One of the striking advantages of electric traction is illustrated by the fact that the adoption of a practically uniform gradient of 3 per cent has made it possible to locate and construct a line but 26.2 miles in length, connecting, through so exceptionally mountainous a country, termini which are 21 miles apart as the crow flies. In accomplishing this result, one tunnel is used; this pierces the Penobscot range, as shown on the profile, and is 2684 ft. in length.

The passenger traffic of the road is chiefly through service, the country between the two cities being sparsely populated. A considerable freight business in delivery of supplies to the inhabitants

of the intervening country and in hauling farm produce to market as well as a moderate express business has been developed since the service of this road was inaugurated.

The railway is constructed upon a private right of way 60 ft. wide, fenced on both sides throughout its entire length. Grade crossings are entirely eliminated, a feature of construction which may well be copied wherever and whenever possible, the resultant increase in speed compensating in large degree if not wholly for the increased cost of construction. There are 33 bridges crossing highways and streams; the majority of these structures have concrete abutments and steel girders. There is one three-arch bridge of granite masonry, and one bridge using steel girders supported upon high masonry piers. The track rail is a Boston & Albany section, weighing 95 lbs. to the yard and is supported upon 8-ft. ties spaced to 24-in. centers. Every fifth tie is 9 ft. long, the extended ends of these ties carrying the insulators which support the contact rail. The ties are laid upon a bed of anthracite coal cinders topped with a dressing of broken stone. All curves are carefully compounded, and the outer rail properly elevated with reference to high speed service.

The contact rails are 60 ft. in length and weigh 80 lbs. per yard. The specified composition of the contact rail is as follows:

Carbon not to exceed .10 per cent; manganese, .55 per cent; phosphorus, .08 per cent; sulphur, .10 per cent; silicon, .03 per cent. Its conductivity is equivalent to pure copper having about one-eighth its cross-section. The center line of the contact rail is 28 ins. from gauge line of the track, and its upper face is 5 ins. above the track rail, this location being selected to permit operation of steam locomotives over the track without disturbance of the contact rail or its guard. Fig. 3 shows relative position of the track rails, contact rail, the rail guard and collecting shoe.

Each 60-ft. length of the contract rail is anchored at its middle by a projection of the malleable iron casting at the top of the insulator, which projection engages with a slot in the base of the rail. To allow for expansion, adjacent rails are separated by a distance of 1/4-in. when temperature of the rail is 60 deg. F. To permit free expansion and contraction, the fish plates are left sufficiently loose. Contact rail and track rails are electrically connected throughout their respective lengths by copper bonds which are soldered to the rails. These bonds are fastened under the base

of the rail. The rail guard is a 2-in. pine plank, 6 ins. in width, supported directly over the rail by oak posts at intervals of 8 ft., these posts in turn being supported by the contact rail to which they are attached by means of malleable iron castings and hook bolts, as shown in Fig. 3.

The schedule provided for in the equipment of the road contemplated an hourly express service and a local service upon headway of 90 minutes. The rolling stock equipment comprises six combination coaches, each having a passenger compartment, a

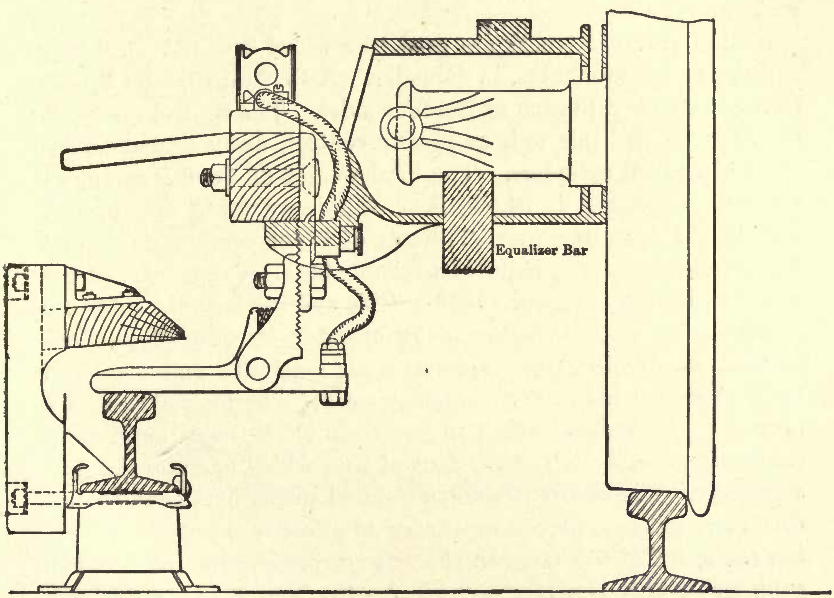


FIG. 3. — CONTACT SHOE AND GUARD-RAIL.

baggage compartment and a toilet-room. The passenger compartment provides 38 seats of standard Pennsylvania passenger car size, i. e., 40 ins. long; while eight seats are provided in the baggage compartment, which is also used as a smoking compartment. The general dimensions of the car are: Length over end panels, 43 ft.; over platform, 51 ft.; width over outside sheathing, 9 ft. 6 ins.; height from bottom of sill over roof, 9 ft. 8-1/2 ins. Double sliding doors are used at the passenger end of the cars and single sliding doors at the opposite end. Loading steps are used at only one side of each platform, and the side of the platform opposite

these steps is used for the motorman's cab. At each side of the baggage compartment is a sliding door 42 ins. wide; the vestibule side doors are hinged to the vestibule post next the car body, and when closed are locked by the trap door which is lowered to complete the floor of the vestibule and cover the steps when the door is closed.

The cars are equipped with M.C.B. couplers, Gould platforms and two-stem spring buffers. Automatic air sand boxes are used. "Cow-catchers" attached to the trucks are placed at each end of the car and are set back a sufficient distance to avoid interference with the couplings.

Brill No. 27-E-2 trucks are used; the wheel base is 7 ft. 6 ins., and the wheels are 36 ins. in diameter. A General Electric No. 66 motor is attached to each of the four axles. The control system is the Sprague multiple unit automatic control, using contactors instead of control cylinders. The total weight of the car equipped, without passengers, is 84,000 lbs. A railway using cars of this weight and operating over gradients of 3 per cent ranging from 3 to 5 miles in length, requires a reliable brake equipment. In the case described in this paper, both outside and inside brake shoes are provided, the outside brakes being operated by two independent means, viz., Westinghouse automatic air apparatus and a vertical hand wheel located in the motorman's cab. The inside brakes are operated by a vertical wheel in the vestibule through mechanical connection absolutely independent of that which operates the outside shoes. The failure of no one element in the brake equipment, therefore, can deprive the train crew of effective means for checking the speed of the car. In the arrangement of the inside brake equipment, provision is also made for the Newell magnetic track brake which, however, has not yet been developed for cars equipped with motors of so large a size as are used in this instance.

The Westinghouse air-brake apparatus is so arranged as to permit use of the "straight air system," and also of the automatic system. The former, by which air admitted by opening the engineer's valve operates directly upon the piston of the brake cylinder, is generally used for the reason that it readily permits graduated application of the brakes. At the same time, the automatic is available and is brought into service at any time by reduction of the train-line pressure.

The cars are arranged for operation singly or in trains, the multiple-unit control system being adopted with special reference

to possible ultimate operation of trains comprising two or more cars each.

The construction of the contact or collecting shoe is shown in Fig. 4. This design is due to Mr. W. B. Potter, chief engineer of the railway department of the General Electric Company.

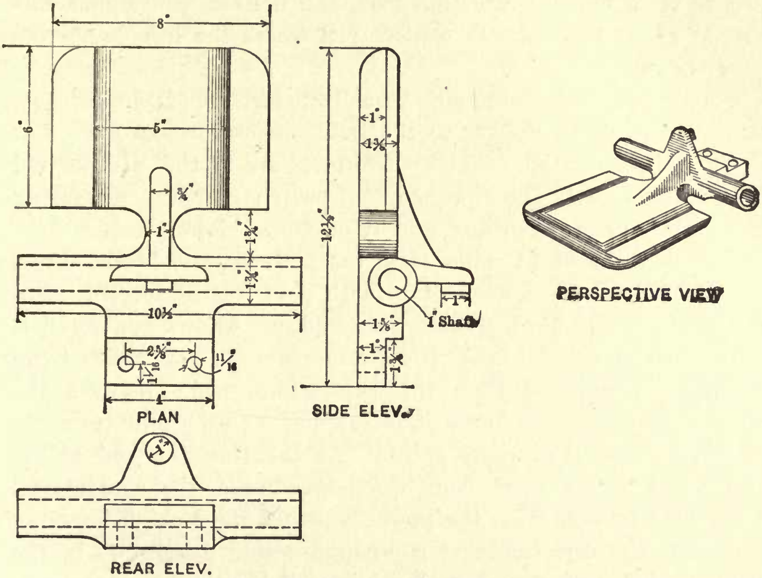


FIG. 4. — PLAN OF THIRD-RAIL SHOE.

The cars are equipped with trolley poles for use in passing over portions of the city traction systems, and the switch which controls the connection to trolley and shoe is arranged to permit change from trolley to third-rail supply or vice versa, without losing contact.

There are perhaps no special features of the power plant to justify a detailed description in this paper. It is located about 8.4 miles from the Hazleton end of the line upon Nescopeck creek. The dimensions of the building are 132 ft. x 84 ft.

The electrical equipment comprises three 400-kw three-phase alternators of the revolving-field type, direct-connected to three single-expansion twin engines, operating at 150 r.p.m. Each engine has two cylinders 18 ins. in diameter and 36 ins. stroke, the cranks being connected 90 deg. apart for the purpose of ob-

taining uniformity of rotation. Fly-wheels, 15 ft. in diameter and weighing 60,000 lbs. each, further facilitate parallel operation, and assist the engines in taking care of sudden variations of the load.

The alternators deliver tri-phase currents at 390 volts. A 400-kw converter, located in the power-house, receives alternating current from the generator bus bars, and delivers continuous current at about 625 volts to contact rail where the line passes the power-house.

Two groups, each comprising three transformers of 150 kw each, connected in delta, deliver to the transmission circuits energy at 15,000 volts potential. The transformers are of the oil-insulated self-cooling type. The equipment of switch gear and measuring instruments present nothing worthy of special description.

At a distance of 11 miles from the power-house, in the direction of Wilkesbarre, a sub-station with electrical equipment, comprising three step-down transformers and one 400-kw converter, is located. The contact rail, from this point to the Wilkesbarre terminus, is supplied from this sub-station, while between the sub-station and power-house it is supplied at each end from the converters located at these points. At the Hazleton end of the line, which is 8.4 miles from the power-house, the contact rail is supplied in part from the power-house of the Lehigh Traction Company, the direct-current compound-wound generators in the plant of that company operating in parallel with the rotary converter at the power-house of the Wilkesbarre & Hazleton Railway.

The alternating-current transmission from power-house to substation — and to a point several miles beyond the latter — employs a potential of 15,000 volts. The circuit comprises three bare copper wires, No. 4 B & S gauge, forming an equilateral triangle 30 ins. on each side. Double-petticoat glass insulators 7 ins. in diameter are used. The poles are spaced 100 ft. on curves and 125 ft. on tangents. Locust pins 7 ins. long and 2 ins. in diameter, where they enter the cross-arm, are used. Two of the pins are carried by the cross-arm, and the third is inserted in the top of the pole, which is clamped with 7-in. iron bands. The yellow-pine cross-arms are 6 ins. x 4½ ins. in section and 34 ins. long. They are secured to the pole by two 5/8 in. bolts. The transmission circuit is transposed twice, each transposition making one-third of a turn.

The transmission circuit is carried to a distance of 14 miles from the power-house in the direction of Wilkesbarre, i. e., about three miles beyond the fixed sub-station at Nuangola. This is done to permit the supply of alternating current to the portable sub-station, which is sometimes located at the end of the transmission circuit.

The portable sub-station comprises a car 36 ft. long and 9 ft. 6 ins. wide, carrying a complete sub-station equipment of electrical apparatus, comprising three 150-kw transformers, one 400-kw converter, and a complete outfit of alternating-current and continuous-current switching apparatus. It is also equipped with lightning arresters and reactance coils. Fig. 5 illustrates the arrangement of the apparatus inside the car. The total weight of the equipment is about 51,000 lbs. The car is not equipped with motors, but, when necessary, is attached to a regular passenger car and hauled to any part of the line where it may be needed. In the operation of the line it serves the double purpose of providing a reserve for the transforming and converting equipment of the power-house and sub-station, and of supplying an additional sub-station, which may be located near the top of the long grade at the Wilkesbarre end of the line when traffic on that part of the system is particularly heavy, as may happen in case of special excursions from the city.

Experience in Operation.

1). *The Contact Rail Guard.*

In operation of the road the guard has repeatedly demonstrated its value in protecting the contact rail against sleet and thereby preventing interruptions of service, which in the severe winter climate of these Pennsylvania mountains would otherwise have been comparatively frequent and serious. During the winter of 1903–04 cars were operated from 6 a. m. until midnight upon headway which at no time was less than one hour, and notwithstanding this infrequent service and the fact that no cars were running between midnight and 6 a. m. there were but two instances in which any serious delay occurred by reason of the formation of sleet on the contact rail. Upon one occasion a car was delayed one hour and 50 minutes, and at another time a car lost, during the round trip, 28 minutes. The trouble occurred on a stretch of track where the

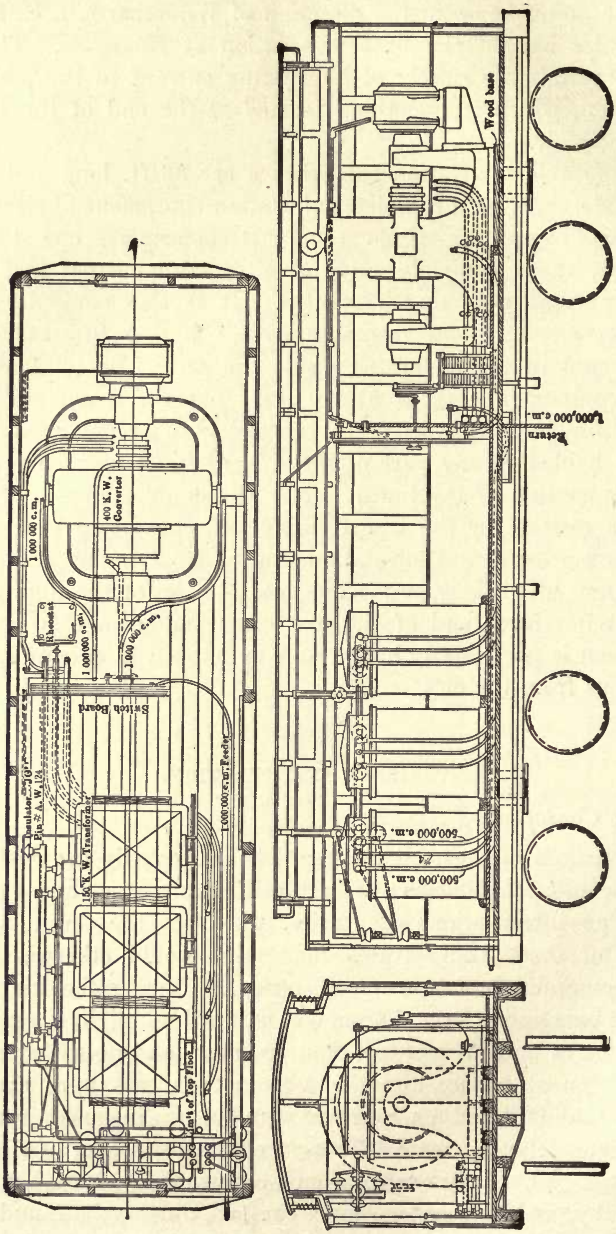


FIG. 5. — CONVERTER CAR.

line is particularly exposed to the sweep of the wind over the mountains. Partial formation of sleet on top of the contact rail which occurred in these cases would have been greatly reduced, if not eliminated, had the guard been even 2 ins. wider. In cases where it is not necessary to consider the possibility of occasional operation of steam rolling stock experience on this road seems to show that effective protection against sleet can be secured by employing a horizontal plank guard substantially as shown in Fig. 3, but extended in each direction, i. e., toward the track and away from it 1 in. farther than the guard adopted in this instance. Where possible operation of steam rolling stock will not permit such extension in the direction of the track, the guard should be widened at least 1 in. in the other direction, i. e., away from the track.

The addition of a vertical plank attached to the posts which carry the top guard would secure effective protection against sleet coming from that side of the track, but on the other hand it would tend to cause the accumulation of snow around and upon the contact rail. Mr. C. B. Houck, superintendent of motive power of the Wilkesbarre & Hazleton Railway, to whose courtesy I am indebted for many particulars regarding operation, attributes the success of the guard in large degree to the fact that it is open front and back, so permitting the wind to drive snow through the space between contact rail and the guard.

2). *The Collecting Shoe.*

The use of a horizontal guard above the contact rail implies necessarily the adoption of a collecting device differing from the familiar link type generally employed in connection with systems of third-rail supply. On the whole, experience in operation of the shoe illustrated in Fig. 3 has been very satisfactory, and in the opinion of the writer has demonstrated the essential superiority of a shoe of this type, particularly at high speeds. Some trouble in breaking shoes has resulted from failure to maintain accurate alignment of contact rail and track rails, as a consequence of which shoes have been broken by striking against the posts which support the guard, and in order to make sure that when the shoe strikes these posts the break shall occur at a predetermined point and not carry away the supporting casting as well as the shoe, it has been deemed advisable to reduce the section of the shoe casting at the

weakest point to the dimensions shown in Fig. 4, which in this respect are considerably modified as compared with the original design. At high speeds the shoe has less tendency to jump than the link type shoe, the moving parts being comparatively light, and the spring pressure — about 15 lbs.— proving more effective than gravity in maintaining contact of shoe and rail. The design of this shoe can with advantage be materially modified in respect to details; in type, however, it is excellent and very satisfactory.

Its ability to collect heavy currents satisfactorily was well demonstrated by a test carried out for the purpose of determining the ability of the electrical equipment of the Wilkesbarre & Hazleton cars to draw a heavy trail car up the mountain grades. In this test a motor car was coupled to a standard Lehigh Valley passenger coach weighing 70,000 lbs. The total weight of the two-car train, including train crews and observers reading the measuring instruments, was 156,000 lbs. Simultaneous readings of current and e.m.f. were taken at 30-second intervals at the power-house and at the permanent sub-station, and similar readings were taken at 15-second intervals on the motor car. At times the speed was determined with a fair degree of accuracy by counting rail joints, although at the higher speeds the results thus obtained are hardly reliable.

The start was made at the Wilkesbarre terminal at 1 a. m., and the run to the Hazleton end of the line was accomplished in 68 minutes, the average speed being 22 miles per hour. During this run the current per motor cars in climbing the long 3 per cent grades exceeded 400 amperes per shoe. The only sparking noted occurred at irregular intervals, averaging perhaps distances of something over a quarter of a mile, and due doubtless to slight differences in elevation of adjacent rail ends. The night was dark and the slightest spark under the shoe was easily detected. At the end of the run the shoes were found to be in good order and not excessively heated.

3). *The Brake Equipment.*

That the brake equipment of some of our electrically operated urban, suburban and interurban lines is inadequate has been demonstrated in recent years by a number of fatal accidents; that similarly unsafe conditions exist in the equipment of many other lines is undoubtedly true. Electric traction is admirably adapted

to operation over heavy grades. Obviously special precautions in respect to brake equipment should be observed where these grades are encountered. The general features of the equipment provided in this instance have been described. In operation they have proved very satisfactory. Where both inside and outside shoes are used it is found advantageous in descending heavy grades to apply one set or the other to the point of actual contact with the wheel, leave this set thus adjusted and use the other set for such additional braking as may be necessary. This method is particularly advantageous where axles and trucks are light in construction, or where from long usage or inadequate maintenance there may be lack of rigidity, and where, consequently, if but one set of brake shoes be applied the braking may become ineffective. The partial application of one set, e. g., the inside shoes, holds the wheel firmly in place, and increases the promptness and effectiveness of results attained in applying the other set of brakes. In the operation of the Wilkesbarre & Hazleton Railway, when a car reaches the top of one of the long grades the conductor takes his place in the vestibule and applies the inside brakes by hand, tightening them just sufficiently to take up the lost motion and bring the shoes into firm contact with the wheels. The motorman then holds the train, usually by applying the air-brake as may be necessary, and in case any part of the brake-rigging of the air-brake apparatus should fail the car can be held by using the inside brakes, which being already in contact with the wheels can be promptly applied.

4). *The Converter Car.*

The practical value of a movable sub-station has been demonstrated a number of times in service. It is a sufficiently effective reserve for the converters located respectively in the power-house and the permanent sub-station at Nuangola, and it has also been used with satisfactory results to increase the supply of continuous current on the long and steep grade which begins at the Wilkesbarre end of the railway.

The speed with which the powerful motor equipments carry up the long and heavy grades cars weighing, with their load, over 90,000 lbs. each is a striking illustration of the possibilities of electric traction in railway work. Upon the occasion of the test with trail car, which has been referred to, the speed of the train

at a point midway between the power-houses at St. Johns and at Hazleton was 28 miles per hour, the grade being 3 per cent, and the weight of the train 156,000 lbs. At points nearer the power-house, the grade being the same, the speed attained was not less than 34 miles an hour.

FRIDAY MORNING SESSION, SEPTEMBER 16.

CHAIRMAN DUNCAN: The session this morning will consist of a discussion, or a continuation of the discussion on the application of alternate motors to railway work, and, if we have time, the reading of a paper by Mr. Parke on "Braking."

DISCUSSION.

I will take the privilege of opening the discussion myself with some remarks on the general subject of the application of electricity to railroads. In the first place, the types of service that electricity has to perfect are tramway service, city-train service, interurban service and trunk-line service. Now, of those types the first three have fallen victims to electricity — tramways, city-train service and interurban service are now operated by electricity. The reason is, of course, that electricity affords better facilities and is cheaper.

Before the road at Richmond, Va., was started in 1887 and 1888, the practical success of electricity as a motive power had been shown. It had been shown that electricity could be applied to the propulsion of cars. It had not been shown that it was practical commercially. That experiment showed it was commercially practical, and from that time in tramways the motive power was rapidly changed to electricity.

What happened in the tramway service was this: A large number of small units were operated from one station; that means that the load factor at the station was good; that means that the load factor on the copper was good, and operated direct currents from one or more stations at a time. When the question of displacing cables came, the situation was more serious. Cable traction was successful; it was economical, and for crowded districts it was hard to see how electricity would replace it. However, the advance electricity made gradually ousted cables from tramway work.

For city-train service, again electricity ran against a harder proposition. The elevated roads were run by steam locomotives. The mechanical arrangements and the investments necessary to change to electric traction were enormous. It was not until the multiple system gave electricity a decided advantage over steam, that electricity was adopted over urban roads. In this city-train service we have the same condition of affairs. We have a large number of units in a small compass, as in the case of the tramway work, and a still larger number of units on one station, a comparatively good load factor for the station, a comparatively good load factor for the copper.

For interurban roads the advantages offered by electricity were very

marked. It opened up a new type of service impossible to be operated by steam. It gave to country districts, the headway of the cars varying from twenty minutes to an hour, a service which it was impossible for steam to give, and the reason of its development was the fact that this service could be economically given. The reason of that, again, was the fact that by successive distribution a large number of units could be fed from one station. The load factor on the main station was good, although the load factor on the sub-stations and on the copper was bad. The load factor on the sub-stations and on the distributing part, the transmission part, on the copper, has been improved, of course, by the use of storage batteries in the sub-stations.

Now, in all of these cases the reasons for the success of electricity lies in the fact that the load factor on the generating station, where the losses are greatest, has been brought to a reasonable figure. The load factor on the sub-stations is not so important in its effects because losses in the sub-stations are not of great importance. The load factor on the copper is of importance, dependent upon the amount of copper used in the distribution of the service to the cars. The load factor on the copper is very bad, of course, but the expenditure for copper is not great.

Now, there is another point to be considered when you come into work like steam-railway service, and that is this: The load factor itself, as a figure, does not tell the whole story by any means. We may have in the same station the same load-factor for two days, and the power per hour may cost the second day twice as much as the first. In the ordinary load we have the load curve, which gives us the amount of power required at different times in the day, and we run our boilers and our generating units, turning them on as the power increases. In the type of load that would be given by railroad work, we do not have a curve that comes up and varies twice a day, but we have a curve that fluctuates greatly from time to time. So a large part of the capacity of the plant must be used all the time. Consequently, it is necessary to introduce another consideration, and that is the cost factor of power. With the same load-factor, the cost factor may differ very much. If we define the cost factor as the ratio of the actual cost per kilowatt-hour delivered to the cost per kilowatt-hour at full load, we will find with the same load factor that the cost factor will vary considerably, for if our boilers have to be operating and ready to give steam at any moment, losses would continually be greater than if the boilers are banked and fire spread only when we need power.

In the same way the cost-factor of our copper varies with the nature of the load factor. If we have a given amount of energy to distribute, and have enough copper to give it 10 per cent. loss, if it is distributed over twenty-four hours, then if we distribute the same amount of energy in twelve hours, the loss is twice as great. So in any situation we must have determined the cost factor in our copper, the cost factor in our sub-station, if we use one, and the cost factor in the main station; and those are figures that are more important than load factors, and dependent not only upon the load factor, but also upon the nature of the load factor.

When we come to trunk-line work, the matter has been discussed and

will be discussed further. Taking for granted the possibilities of single-phase alternating motors, taking for granted voltages which make the copper investments comparatively small, we are in the same condition that we are in the other three types of service. That is, we can put on our generating station, where the losses are greatest, a fair load factor. The type of the load factor, however, will be different from the type of load factor in our ordinary service, and that must be taken into consideration in determining the cost of the power to be used. If we can use high voltages there is no doubt about it, that we can operate steam roads with overhead wires, the voltage being high enough to bring the current down to the quantity that can be collected. But the question is whether there is any great advantage in it.

We have had that fully discussed, and I hope we will have it further discussed, but it seems to me this: We can offer very little to the general railroad man, we can offer very little in the way of decreased expense. We can offer very little in the way of increased facility of operation. We do offer them this, though: We offer them the possibility of a great deal of trouble by using a high tension distributing system, by collecting from a high tension system to feed our road depending for its operation upon a few large units spaced at large distances; that is, at central stations, and then distributing through sub-stations.

It seems to me, so far as the general problem goes, outside of special problems that come up, that we still are not in a position to offer for general railroad work any particular advantage of electricity over steam. There are specific problems, as every one knows, in which electricity has tremendous advantages. Some years ago I investigated for the B. & O. the electrification of a section 100 miles in length, where the steam conditions had become practically impossible. The road was run up to its trackage limit and it curved so that the heaviest locomotives were limited, therefore the weight of the locomotive and therefore the size of the train. Dr. Hutchinson and myself went through that very carefully, and found electricity offered great advantages. There was one grade of seventeen miles of 2½ per cent. and another of fourteen at 2½ per cent. In a case of that kind there is no question of considering the loss in electricity, but by starting at one end and ending at the other there is great advantage in the traffic.

Another advantage Mr. Leonard pointed out is the fact that electricity allows us to increase the length of train with the steam draw-bar conditions. The size of the train is practically limited by draw-bar conditions, and with electricity the train can be very much increased.

I think Dr. Steinmetz took the ground that the reason for the larger train units was the increased economy of large locomotives. That, of course, is not exactly so. The reason for the larger train units is in the economy of the large locomotives and the increased *tractive effort*.

There is very little that electricians to-day, even with the single-phase alternating motor, can offer to railroad people, except assistance in special problems.

Mr. F. J. SPRAGUE: Discussion on this subject seems to be assuming two phases,— first, how to use the alternating current in railway work, and, second, whether trunk lines can be operated by electricity.

This will extend the discussion into a pretty broad field. We can all learn something from the milestones we pass, and in view of the numerous claims which have been made for the alternating-current motor, more particularly of the single-phase type, I would recall some promises made a number of years ago when the continuous-current motor was to be promptly relegated to obscurity. You all remember the early phases of the development of the polyphase motor, and how the commutator was held to be the great bugbear of its rival. The commutatorless motor was to institute a revolution in railway work. Of course it has been applied to stationary purposes most successfully, and two companies in particular, the Ganz and Siemens, have made some effective demonstrations of its possibilities in railway work.

I cannot, however, but feel that the multiplicity of conductors is a practical bar toward any widespread application of this system. The position I take is not a new one. In 1888, when the question of equipment of the West End Railway of Boston was under consideration, and the Bell Telephone Company with all its power attempted to prevent the use of the rails for return circuits, the president of that road had to consider very seriously whether they would use two trolley wires. I objected to it as strongly as possible, and the modern trolley has been developed on the idea that one wire overhead is quite sufficient,— oftentimes too many, perhaps.

And so, I think, in the alternating-current development, we shall proceed on the basis that one conductor overhead is all that we can stand. If the experiments made demonstrate anything at all, it is the impracticability of operating general trunk lines on the polyphase system.

Now, after all these years and the various promises that have been made on behalf of the polyphase type of motor, we find in the series single-phase motor a reversal of practice, and the adoption of many of the features of continuous-current motors. The much-abused commutator has reappeared in a more unsatisfactory form, and the field windings are more complicated. I think I am safe in saying, that not only at present, but for all time to come,— prophecies are dangerous, but I think I will stand pat on this one — the continuous-current motor, measured by all qualities,— weight, efficiency, simplicity, reliability and cost of maintenance, can claim superiority over the alternating-current motor of the single-phase type.

Why, then, are we striving for the development of the latter machine? It is not because it is necessary in street-car service or in elevated railway or underground work, or for limited distances on interurban roads, but to reduce on long distances, and especially heavy traction the prime investment for line equipment, and the investment in the moving parts at the sub-stations.

Just here I may point out that people are apt to somewhat exaggerate the saving to be effected. Any road which extends over a considerable territory and operates from sub-stations may be considered merely as a series of connected railways operated from small central stations, each of which, instead of being steam-equipped, is run directly by a current transmitted from one central source. Increase the working potential and the

distance between these small stations can of course be increased. The ordinary limit for continuous current work has been primarily determined by the limits of successful commutation for a single motor, but by operating two in series on four motor equipments the limit can be at once doubled,—to say nothing of other possibilities. When we put an alternating current directly upon the working conductor we run into certain possible difficulties. In the first place, the distance between the stations cannot be increased in that ratio which at first sight would appear. Whatever the maximum limit on the trolley wire, the average potential is of course much less, and the resistance of iron rails to the passage of an alternating current is much higher than for the continuous. It can be safely said that with any given size of trolley wire, and average load per unit distance, the distance between the sub-stations on an alternate-current proposition would not by any possibility increase in the same ratio as the increase of maximum potential, when compared with continuous-current equipment, nor even directly as the ratio of increase of its own potential, alternating-current propositions alone being considered.

In the operation of a single-phase alternating-current motor I fear that we have not passed through that period of time, or those conditions of service, which will develop certain conditions, some possibly dangerous and some irritable. In the earlier days of electric railroading probably most of us have at times noticed the possibility of shock,—and that with only 400 or 500 volts,—due to leakages on the car and a break between the metal of the car and the rails or the ground, when a passenger on moist ground made a contact in taking hold of the handrail. That experience leads to a possibility in high tension work which is not entirely agreeable to contemplate, and against which the utmost precaution must be taken.

We must, if we are going to have high-tension transmission on the trolley, bring that high tension into the car. It matters not whether we are going to use high tension direct on the motor circuit, or whether we are going to use a transformer and reduce it, the high tension must come in somewhere. This high-tension alternating circuit has a greater tendency to break down insulation, and it must of course be protected by an iron or lead shield which must be put in connection with the metal frame of the car. In time the gradual deterioration of the insulation may, in fact, it most likely will, lead to a partial or perhaps a complete break-down, bringing the whole metal frame into potential relation with the incoming current.

Fortunately, in most propositions for alternating-current work heavy cars are used which most of the time will make good rail contact, but we can easily see that at times on dirty or sleety tracks there may arise a condition in which there is a decided difference of potential between the frame of the car and the ground. That leads to possible dangerous conditions, and will require the utmost care on the part of engineers who are installing electric equipment on alternating-current circuits.

There is another condition to be considered. Fifty times a second the potential passes zero, and current ceases. When running with a continuous current, circuit can often be maintained even through bad rail

contacts, but under this latter condition there seems a liability of a greater aggregate period of interruption of current in an alternating-current equipment than there is on the continuous current.

The question whether electricity should be used on trunk lines is such a big one that discussion would be almost endless. As the chairman has pointed out, there are special conditions, such as characterize sections of mountain roads and terminals,— where electricity should be seriously considered; and there are certain congested conditions on some railroads, and especially some of the foreign lines, where it is almost impossible to extend terminal facilities, which call for electric operation. But, as I stated at the general meeting of the Congress the other day, I think that a great deal of the money which may be available to a trunk-line system would be often spent in protecting its territory rather than changing equipment.

When the electric railroad was first introduced, of course everybody sought franchises. Many people got them, and, as usual in this country, at a very low cost. They have often pre-empted the territory parallel to steam railroads, have created a business of their own, and are in position to divert business from the steam roads. As such they are commercial propositions which can very easily be investigated, and no one should be better qualified to investigate these propositions than the steam railroad owners and managers. If I had a railway running between two points, with termini and roadbed well established, and somebody built a road alongside of me,— it matters not whether steam or electric,— and created a special business besides diverting my traffic, I would, if I could on fair terms, get control of it. I would not try to duplicate a special traffic on a system that was not fitted for it. And so I think that the policy which I see by the public press is being more or less adopted by the New York Central and some other railroads of buying up properties adjacent to them, which cannot be duplicated and which have already created business of their own, is one which, commercially speaking, is by long odds one of the best things the trunk line management can do.

In foreign countries, where there is not that freedom of granting franchises, and where the local conditions do not permit quite that interurban service that we have here, necessity dictated by competition is of course less, but the congestion of roads that terminate in cities like London is creating special conditions calling for a change of equipment.

A good many people, noting that the Pennsylvania and the New York Central systems are adopting electricity in New York, have jumped to the conclusion that this meant the end of steam on trunk lines. It distinctly does not. The Pennsylvania road had to get into the city of New York and connect through to New England and Long Island. There was no possible way save to go underground, and the only way they could then handle their trains successfully was by electricity, irrespective of cost — that was a matter of secondary consideration. It does not follow that the Pennsylvania is going to extend electricity on all its trunk lines, and it won't do it for a good many years.

The New York Central is somewhat similarly situated. It enters New York city through a tunnel. A terrible disaster in which a number of people lost their lives focussed upon the road an expression of public

opinion which could not be answered except in one way — prompt assent to legislation that steam road power should be abandoned; and when the determination was made to abandon it, it could not be limited in territory to that required by law. To make this clear I will repeat details given at another session. Most of you know that Manhattan proper is bounded on the north by the Harlem river, only a few miles from the main terminal at Forty-second Street. Some distance above this the trains of the main and Harlem divisions, as well as the trains of the New York, New Haven & Hartford lines, converge, and come into the main station over the New York & Harlem Railroad. It was simply impossible to stop equipment on this stem. Furthermore, in adopting electricity it was also important to consider not only the requirements of the law but the effect upon suburban service, and also upon the general service in the same territory. The territory to be at present operated and the system to be adopted were matters of grave debate. The propositions made by the various companies, which included both continuous and alternating-current work, had to be carefully considered. The great expense of electrification beyond the actual legal requirement, at a time when all railway properties were at a low ebb in their finances, was a serious one, so we finally settled it something after this fashion: The law said: "You must abandon steam." The alternative of course was electricity. "You must go beyond the tunnel." Going beyond the tunnel took us to the neck of a bottle, and we had to get out of it. Suburban lines were being electrified, and outlying competition was ahead. Great elevated and underground railroads existed, and the possible relation of their traffic to that of the Central must be considered. So we decided that in the first place we would have to go above the Harlem river somewhere, and then came the question of location of terminals; and these had to be considered with relation to the balance of the traffic of the railroad — long distance as well as suburban traffic,— and also in connection with property and geographical conditions.

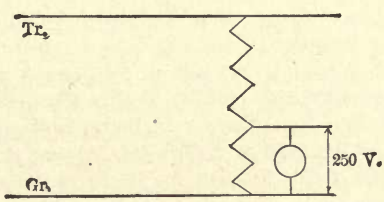
It was finally decided that all suburban service within a radius of an hour's run from New York, this, fortunately corresponding to the best terminal possibilities, should be made electric; and when that was decided it was only reasonable to abandon the idea of maintaining two services and three sets of terminals on the same tracks in the same territory, and logic required that all through trains within that district should be likewise handled in the same manner.

The two problems were somewhat different, of course. The result was finally an agreement that for a distance of about twenty-five miles on the Harlem division, and for about thirty-five miles on the main line, electricity should be used. And these decisions, let me say, gentlemen, have no bearing whatever upon what may be done beyond these points in the future; nor will anything that is done in the future, nor any development which takes place alter in my mind the wisdom of the decision which has already been made. In fact, no other decision was practicable at the time. There was not a company in the world prepared at that time to do anything else than supply continuous-current motors to perform the service which would be required by a road where 700 train movements a day must be maintained without excuse, delay, or explanation.

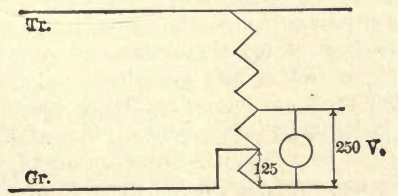
SECRETARY ARMSTRONG: Mr. Sprague touched on one point to which I would like to call attention to, and that is the safety on an ordinary tram car having a potential on its trolley of 2000 volts or more, and I would ask Mr. Lamme or Mr. Lincoln if they have anything to say in connection with this point.

MR. LAMME: There are several points brought up in Mr. Sprague's discussion of this subject on which I would like to speak further. He intimates that in a number of ways the direct-current motor will always be superior to the alternating-current motor. There is one point in which the alternating-current motor will be superior to the direct-current motor, and that is in the voltage which can be utilized directly on the motor. The direct-current railway motor will always necessarily be a high-voltage machine. We cannot use 200 or 250 volts advantageously on railway service with direct-current motors, but we can use it on the alternating motors, because with the alternating current we have a simple means of transforming the voltage from that supplied by the trolley to whatever is necessary for the motors. The high voltage on the direct-current railway motor is a source of weakness in practice, and in this particular point the alternating-current motor wound for low voltage will be superior.

There is a second point of superiority in the use of such motors when operated from a transformer on the car, viz., by means of a certain arrangement of the taps on the transformer, we can reduce the maximum voltage from the motor to the ground to one-half that used on the motor. For



example let us consider an arrangement of transformer and motor as illustrated in diagram No. 1. Connecting a 250-volt motor across the secondary of this transformer we get from motor to ground a maximum stress of 250 volts; but if the ground terminal of the transformer is



tapped at a point midway between the two secondary terminals, as illustrated in the second diagram, then we get 125 volts maximum to the

ground. With this arrangement with two motors in series for 500 volts, we would get 250 volts to the ground instead of 500 as with direct current. This illustrates one of the advantages which can be obtained by the alternating-current motor over the direct-current, and it will serve to eliminate considerable trouble due to break-down of the insulation on the motor.

In regard to the difficulties which we will find in the development of the single-phase alternating-current system, I would say that we are not starting in under the same conditions as Mr. Sprague encountered in his Richmond line and his other early roads. At that time comparatively nothing was known about proper designs of railway apparatus and there was practically no experience to fall back upon. But the alternating motor now comes at a time when we have had many years of experience in electric railway work, and this is going to make a great difference in the development of the single-phase system. If, for example, in 1887 or 1888, we had undertaken the design of the large alternators of the Manhattan system of New York city, we would have had an undertaking which it would have been practically impossible to carry through at that date. But at the present time we are ready and willing to undertake generating machinery of much greater difficulty than the Manhattan generators. In the same way, the alternating-current motor now comes at a time when we have had all these years of experience on railway work, and we will be able to avoid a great many difficulties which developed in the direct-current railway system and which took years of experience to find out and eliminate.

As to the question of danger from high-tension trolley lines, I think it will be found to be true that there would be a greater possibility of open circuits and of shocks on a 250-volt direct-current railway circuit, for instance, than from a 500-volt circuit, because the higher voltage is more liable to break through from the car to the ground and thus ground the frame of the car. With 2000 or 3000 volts, I think it will be almost impossible to break the circuit between the frame of the car and the ground, because such voltages will spark through any ordinary separating or insulating medium on the track, and thus close the circuit. In other words, the higher the voltage from trolley to ground, the less liable is the circuit to be opened between the car and the ground.

There is one point which has not been brought out before in these discussions, which may have important bearing on the application of alternating-current motors to city work. A statement was made, in one of the discussions, that the cities would probably maintain direct current for their service, and that the field of the alternating-current motor would be in suburban service. If you look at only one part of the problem that might appear to be true, but there are certain conditions which may be of great future importance in deciding this question. One of these features, of which nothing has been said in these discussions, and which may have a great deal of influence some day, is the question of electrolysis. This question has come up in a number of cases and we know that railway people are thinking about it. It may be a serious question some day in the cities. We have made some elaborate tests to determine the electrolytic action

of alternating currents, and while these tests have shown that the alternating current has a slight action, yet in general, with the same current it was found to be less than 1 per cent of that of the direct current. This feature may have a controlling influence in the adoption of alternating-current motors for city work. I know that in certain European cities this matter is coming forward rapidly and certain European engineers have told us that they will be obliged to adopt alternating current on their railway lines within a comparatively short time on account of difficulties from electrolysis with their direct-current systems.

It has been mentioned that the character of the load on an alternating-current railway system is different from that of the direct-current system. It is different in several ways. The proportion of load in the power-house will differ from that of the direct-current system, because in starting and accelerating, the load will be to a certain extent inductive, which represents no energy. This inductive element, while not representing energy, does represent torque. Therefore in starting and at low-speeds while accelerating, a considerable proportion of the current supplied to the car represents no energy and, therefore, represents no energy load on the power station. In this feature, the single-phase system resembles the present locomotive system in taking least power at start, with the amount of power increasing as the speed increases. If there were no losses in the motor itself and the control system, then the car would start with zero energy, and the energy consumed would rise proportional to the power actually consumed in accelerating and driving the car. This would be true only when potential control is used and all rheostats are omitted.

This inductive load taken by the motors at start will have very much the same effect on the alternating-current generators as if an energy load were carried, but represents an extremely small additional power required to drive the generator. This load also has an effect on the regulation of the generators. But experience has shown that this regulation can be taken care of very readily by means of voltage regulators in the generating plant. Such voltage regulators are very satisfactory for railway service and can operate sufficiently rapidly to hold an average constant potential, although it may not be exactly constant; but in general the regulator will maintain as good regulation at the generator as is obtained in direct-current railway service by means of the series coils.

On the question of polyphase motors for railway service, it has been brought out repeatedly before the American Institute of Electrical Engineers, that American engineers do not consider, and have not considered, the polyphase motor a satisfactory one for railway service, largely on account of the characteristics of the motor itself, and also on account of the two overhead conductors. A European engineer told me some time ago that he had made a careful investigation of the question of polyphase railways in Europe. He stated that in some of the railways where a single trolley was used with two wheels or rollers, the question of keeping the two overhead conductors exactly parallel to each other seemed to him to be an almost insurmountable difficulty, and that while it was being done in a number of instances, he did not consider it practical, and he would not have any arrangement that required as much careful ad-

justment as is required in these cases. This man was a mechanical engineer rather than electrical, and his criticisms were mostly on the mechanical construction. I have had no experience myself with such an arrangement, but it seems to me that with two overhead trolley wires it would be advisable to have two trolley poles with independent movement. I do not believe that the polyphase system will ever come into extensive use in this country, as the characteristics of the motors themselves will prohibit it.

In connection with the use of the single-phase alternating current on heavy railway service, I happen to know that in the case of some of the larger railways in this country, many of the engineers are fully convinced that they will be obliged to transform their roads to the electric system in a very few years' time, and many of them believe that an alternating system will be adopted. The Pennsylvania Railroad Company adopted direct current for their New York terminal, but a number of their engineers are not sure whether they have done the right thing in adopting direct current. They have adopted direct current for very much the same reason as given by Mr. Sprague in the case of the New York Central, viz., it was something which has been tried and proved to be operative. Nevertheless, a number of these engineers feel that by the time the direct-current system is completely installed on the New York terminus, they will find they should have adopted the alternating system. But they are in the same position as a number of the street railways many years ago in regard to the use of the cable system instead of the electric system; in some instances the cable system was adopted, as it was known to be an operative one, while at the same time the engineers felt that the cable system would have to be taken out in a very few years' time. It has been cited, in the adoption of direct current on the above-named steam roads, that as it proved an advisable method to install the cable system, even with the expectation of throwing it out later, so will it prove to be advisable to install direct current on the railway terminals with the expectation of changing later to the alternating. As stated before, many of the engineers are satisfied they will throw out the direct current before many years, and they recognize that a fundamental reason for making the change will appear when they begin to extend their system, and they see, before the terminal system is in entire operation, that the advisability for extension must be considered.

Mr. E. Kilburn Scott: I think that the question of working main lines and suburban lines we will have to settle from the standpoint of the ordinary mechanical locomotive engineer, and I cannot conceive of ten of those men being brought in front of a three-phase motor on the one hand and a single-phase motor on the other, with a commutator, or a direct motor, not seeing or think that the three-phase motor was the thing. That kind of man has more respect for the three-phase than we have. We have seen it grow from a crude apparatus to the perfect piece of work, but it seems to me it is very complicated, and I cannot conceive for a moment of the ordinary mechanical engineers considering the commutator machine. The thing that will decide them in England will be absolute simplicity of apparatus and safety of human life, and on the question of

simplicity, the three-phase motor without any commutator it seems to me has the advantage.

On the question of human life, while we have got the three-wire system, it has come over to us with the commutator and we do not like it. We would rather have less efficiency and a more stable machine. Regarding the third rail, we have it as I say — what we call experimenting with it. That is about as far as we go, because I am sure if we kill off very many men on the Northwestern Road there will be such an outcry in the papers that we will have to give it up. Because we consider human life. In our country, we do not have what I see here and which it amazes me to see, we do not have railway lines running along streets with only level crossings. We do not have railway trains running over surface tramway lines. We do not have that; so we do not have that problem regarding the combination of single-phase and direct currents.

Now, take the three-phase motor again. I raised this point the other day and it was not answered. In a single-phase motor surely you have the current going to maximum and back to zero again and again to maximum. It seems to me if you had to take a fair test, say a locomotive equipped with the three-phase motor and one equipped with the single-phase and commutator, it seems to me, to draw a certain train of a certain weight, say ten tons. you would require a heavier locomotive in the case of the single-phase than you would in the three-phase. I have not that answer. Suppose it was five to one, the usual ratio, that is to say, ten would require a fifty-ton locomotive, a fifty-ton three-phase locomotive draws this. I think if it were equipped with a single-phase commutator it would have great difficulty.

Suppose you are on a steep grade, the brakes are down. You know when you start your steam locomotive you release your brake. Now, suppose the train was very heavy and suppose the train brakes did not come off, wouldn't this be the condition of the single-phase commutator motor? It would be standing still and would have full voltage and full current in the motor, the armature would be going as a static transformer, and the coils underneath the brushes being on short-circuit. Wouldn't you get breakages of the current through those brushes?

We used to make a single-phase commutator motor, and we struggled for nearly a year, but threw it out, because — we used to make it go all right, and then some person would tack it onto a very heavy machine that wouldn't start and try to get a short-circuit through those coils underneath those brushes, and the thing would burn out. And we couldn't go on like this, and we couldn't make a single-phase motor that would work, and don't make them for actual work.

In regard to variation of speed, we hear a great deal about variation of speed and control and arrest and all that. Now, if I want a machine, a motor to drive a Hoe printing press, where I want the machine to go very, very slowly, to get the thing in shape to start I go to Mr. Leonard, I buy one of his apparatus and I have a thing that will crawl, and under certain conditions run to speed. But we do not want a train to go slowly, and we are compelled to rely on the three-phase motor in the operation of trains.

Now, in regard to copper, this of course is a difficulty. We have the two arms as against the single wire, but if you take a high tension system like the Oerlikon, it uses three wires. There is one more wire in that, but isn't that a very condition where you have to give something in order to obtain results? Isn't this the case, that you have a certain amount of bare wire overhead, or a certain amount of insulated wire underground? Now then, if you have a system which calls for more wire overhead, certainly you are better off. You have much less wire underground and it is the insulated wire that runs away with the money.

Then looking at it from the point of the crossings, and that sort of thing. I know that you claim in the three-phase there is danger in the wires going over; but I think on nearly all of these surface systems we are talking about there are ways of protecting all these difficult crossings. If you want to give a speed of eighty or ninety miles an hour you cannot have curves. We cannot run on our present tracks eighty or ninety miles an hour. The inclination of the rails on some curves would be so great that if a train stopped on that particular point it would topple over. We shall have to straighten out our tracks and take away those difficult crossings before we can run that speed. Then you see all the objections to the three-phase disappear.

Anyway, there is this point in favor of the three-phase as against the single: That is, if you have a three-phase and one of them breaks down, you have a reserve in the system. If you have a single-phase and it breaks down it is gone, and if you have another single-phase you have got to switch it in or leave it in all the time, but as I say, if you have a three-phase system and one of them breaks down, the other two carry the load.

Regarding loss of time in shifting, owing to the fact that you are running with a three-phase motor with alternating currents, the traffic superintendent knows that that train is going to go along that track at a certain speed. It may have a greater speed going up an incline, but the fact he knows that that driver must run across the track. Being driven by a three-phase motor is an advantage I think in traffic work. Suppose the train got behind time, and to make that up of course the three-phase motor can make over-speed, and the traffic people I have spoken to about it — steam locomotive traffic people — don't see much trouble there.

At any rate, in this matter I really think that although there has been a great deal said here about single-phase, because the two big companies in this country decide on single-phase, it does not settle the question. There is a good deal to be said on the other side. Dr. Steinmetz said that our three-phase systems in Europe were on a level not far from perfection, and every company has received permission, or, rather, been asked by the government, to extend their lines. Do you think the Italian government would have asked the Ganz Company to extend that line unless it was a magnificent success? It is a magnificent success.

Mr. H. Ward Leonard: For thirteen years I have urged, and I wish to urge once more, an electric railway system having the features which characterize the system identified with my name: First, single-phase high-tension generation, transmission, and conduction by moving contact upon the train. Second, means on the train for deriving in a local, sepa-

rate, insulated working circuit a current of lower voltage which is supplied to the propelling motors. Third, means on the train for varying from zero to the maximum, and without waste energy, the working electromotive force in the local circuit. I think I am safe in saying that nearly all modern single-phase systems have these essential features.

For passenger service, and for light freight and express service, the variable-speed single-phase alternating-current motor may be found sufficiently satisfactory, but for the heaviest freight service I am more confident than ever before that it will be necessary to transform upon the train the single-phase energy into continuous-current, variable-voltage energy and supply it to direct-current propelling motors, as I have urged continuously since 1891.

As a large number of engineers who are attending here have asked me as to the progress that I am making with this system of mine, I will mention some points in connection with it. I first publicly described this system in a patent in 1891, and I read a paper entitled "How Shall We Operate an Electric Railway Extending 100 Miles from the Power Station" in 1894 before the American Institute of Electrical Engineers. The first recognition of the system came from Col. Crompton, who in his presidential address before the Institution of Electrical Engineers of Great Britain, in 1895, I think, predicted that it had features which would give it great importance in electric traction work. Mr. Huber of the Oerlikon Company, in 1902, and Mr. Mordey of Great Britain in 1902, after analyzing the traction problem carefully, concluded that this system was the only one that had been proposed which gave commercial promise. The Oerlikon Company took a license under my patents in 1902, and proceeded to construct a locomotive which since then has been tested.

In 1902 the celebrated engineer of Sweden, Dahlander, as the head of a commission appointed by the Crown to investigate the question whether electric traction could supplant steam traction on 3,000 miles of railway owned by the government of Sweden, after giving careful consideration to the matter, first eliminated the continuous current for transmission; and second eliminated all but single-phase alternating current for transmission; and finally, after considering the systems that had been proposed to that date, reported in favor of my system. And after giving consideration to the cost of installation and of maintenance and of depreciation and operation, and after providing a sinking fund at the rate of 3 per cent per annum to retire the bonds which would be issued therefor, thus retiring the first cost of investment in thirty-three years, they concluded that my system would show a saving to the government of Sweden of $2,000,000 per annum over existing methods of operation by steam. This is the same system, I may say, that the General Electric Company had reported upon by three engineers twelve years ago, and each of the three engineers condemned the system, and each for a different reason.

The first engineer condemned it on the score that the transmission and utilization of single-phase alternating-current energy at any such voltage as I proposed — which was from 10,000 to 20,000 volts — was absurd and beyond consideration. The second engineer decided that I evidently had

given no consideration to the question of sparking, and that it was utterly impossible to operate a system such as I proposed on account of the disastrous sparking. The third engineer reported that I evidently intended to use some very complex mechanism in restoration of energy into the line, and nothing but the use of very complex mechanism would enable me to restore the energy into the line, and, therefore, that this feature was without real value.

As to the application of this system which may have a bearing upon its possibilities for railways, I may say it has been operated successfully in a number of instances upon elevators since 1891 with the most striking freedom from depreciation and a most striking reliability in service, and a perfection of control in starting and making a landing, which is so important in elevator service.

In 1893, I think it was, the Heilman locomotives made use of this system of mine, and although the Heilman locomotive, on account of its enormous weight, proved a failure, it demonstrated that a locomotive of that size could be operated, and was operated, with perfectly satisfactory results as regards control and performance of the commutator for the large generator necessary for such a large locomotive.

About 1893, this system was first installed upon the turrets of the United States Navy, and to-day no other system is used for the operation of turrets in our navy. Great Britain has quite recently decided to try it; it has been recently installed upon a British battle-ship "The Terrible." Those turrets are, I think, quite comparable with the service which is to be expected in the handling of heavy freight trains. One of these turrets weighs 600 tons. It has to be accelerated, controlled, retarded and reversed, and that enormous mass is a thing which presents the greatest difficulty in handling, and the system has given perfect satisfaction and no other system has been employed.

The moving platform at the Paris Exposition probably represents the largest mass which has ever been accelerated and handled and controlled, under single control, by electricity, and that moving platform employed my system of control. It weighed about 3600 tons. It was practically equivalent to a freight train upon a level track with a very great number of curves. It had to be brought to full stop and run at full speed, and it was accelerated every day. Now, in the case of that moving platform, there was a clear demonstration of the fact that a freight train with my system, not only from theory, but from actual current and voltage readings, would be and could be in practice brought from rest to full speed with an amount of energy which under no conditions would be greater than the energy required at full speed. The watts during the period of acceleration were always less than the watts at full speed. I repeatedly took the readings at the installation and have those figures for anybody who is interested.

Other applications that have been made since then are automatic pumping, to maintain certain definite pressure — the rate of pumping being automatically governed by the work performed; electric automobiles, in which the source of power is a gasoline engine on board with my system for the transmission; electric trains such as are now being operated at England

in which my system is employed for electric transmission from a gas engine on the train; and one of the finest, if not perhaps the finest building in New York city, the *Times Building*, is now about to start in operation with my system as applied to high-speed passenger elevators.

The Oerlikon locomotive, which was tested in May, 1904, this present year, of course represents the thing which is most pertinent. In that locomotive, the transmission line employs single-phase 14,000 volts; the entire control is by means of one lever, in starting, stopping, reversing, braking, etc. That locomotive was tested in the presence of a large number of engineers, and a great many engineers from this country received invitations to be present at the trial. The locomotive was tested to a point — and I don't know but further, but I do know it was tested as far as this — that the current in the secondary circuit was double the normal current of the rated horse-power. That is, that amount of current was available without any difficulty whatever as regards commutation.

In this connection, I wish to speak of the weight and cost of the motor generator by comparison with the weight and cost of the necessary motor generator for the sub-station. I wish to point out that in my system the motor generator has to provide only the power sufficient for the movement of the train upon which it is located. It is not necessary, as in the case of sub-stations, to provide, for emergency purposes, several times as much capacity in the converter as the average service would require.

Mr. Sprague incidentally mentioned in discussing another paper, the other day, the probable necessity in the case of the New York Central of installing storage batteries in order that he might get a fairly uniform load upon the sub-stations, as there was a probability at all times of there being four trains in a section to be supplied by a sub-station, and at other times no train. This I think will emphasize clearly the importance of having the energy transformer on the train, where it can be all the time loaded and operated at a good load-factor, and where the first cost will not have to be several times as much as that required by the average demand.

The well-known difficulty of controlling large motors by opening circuits carrying the energy of perhaps 1000 horse-power is going to increase very rapidly as the amount of the power increases. There is some difficulty in opening a circuit of 100 watts; it is worse at 1000 and much worse at 100,000, and it becomes more and more difficult as you go up. And I am not surprised to notice that the best engineers in the various countries are to-day attempting to avoid that difficulty and secure the speed control by voltage control rather than by opening circuits and adjustments of circuits and resistances.

Another point that is of great importance in this connection is the multiple control of a number of units; and here again we meet with great difficulty in attempting to open these circuits. We also meet with great difficulties due to the size of the conductors that must be carried along the train to carry a working current to the motors distributed through a long train. In the case of my system the size of the wires will be determined by the current which the field only has to carry.

There will be three wires that carry only field current, and there will be no automatic switches and no control of controllers.

The restoration of energy is a matter which is as old, almost, as the art, in discussions. So far as I am aware my system is the only one which does restore energy from the condition of full speed to the condition of rest. And I wish to emphasize the point that of course it becomes necessary that we have an energy transformation in order that we can take advantage of the energy of retardation, while it is falling from maximum to minimum, and continue to transform that energy into electric energy having a voltage sufficiently high to force energy into the line. A point of the greatest importance in all of these problems is the frequency. In order to make a commercial single-phase alternating-current motor, we are being driven step by step to lower and lower frequencies. We all know the disadvantages of low frequencies for lighting purposes. A comprehensive system generating a form of energy which can be used for all classes of light and power is of the greatest importance.

This Oerlikon locomotive is the first single-phase locomotive which has been designed for standard railway service, and the condition of the matter now stands in this way: It has been approved by the government of Switzerland, which has tested it, and authority has been given to the Oerlikon works to extend this system to the first section of the line which is to be equipped.

I appreciate fully the fact that a combination of patents and policy is always likely to make inertia in this country, and the General Electric and the Westinghouse companies, so far as concerns patents and as concerns electric railway policy, are practically in combination. It is the greatest difficulty for engineers of this country to receive any consideration for a railway system which is going to affect the existing policy as regards patents and business methods. And that is the reason, which no doubt many of the foreigners are very much surprised to note, that my system is considered favorably by leading engineers of Sweden, Switzerland, Great Britain, and France, and yet is not used in this country. The query is naturally made, if this system has any merit, why isn't it used in America? I think you have the answer in my remarks as to the inertia of a combination of patents and policy of such overwhelming size in any one country.

Of course, this is again an explanation of why the General Electric Company and the Westinghouse Company are so desirous of securing a motor, notwithstanding its immense disadvantages as to control, which has the one advantage that they can go to their former customers who have bought from them 500,000 kilowatts already installed, and say to them that their past assurances as to the permanency of the investment they have made can be realized. I can imagine that it would be rather embarrassing for a salesman to meet a gentleman whom last year and year before they had assured that if they bought the three-phase transmission and rotary with sub-station and series-parallel control of the series motor, that it was unalterable as far as they could see, absolutely permanent, and as good an investment as a gold dollar,— to have to go to

these same investors two years later and say that system is all absolutely wrong, and that the real thing is the single-phase transmission, transformation to lower voltage in a local circuit on the car, and a voltage speed control instead of the series-parallel control.

Naturally this would be a very embarrassing situation from a commercial standpoint,— and they don't say that.

What they do say is "We have devised a system which will enable you to operate with either alternate or continuous current in the same motor and this has the advantage that you can use the 500,000 kilowatts capacity that you have already paid us for."

Now, that, of course, is very good business on the part of the General Electric and Westinghouse, and I am not criticising them in any way as to their business policy. I am merely indicating that the existing patent combination naturally interferes with the development and use of the best ideas. I need hardly say that had Mr. Huber been in the employ of either of the principal companies of this country, my system would not be installed now.

As to some remarks made by Mr. Sprague, I should like to touch on one or two points. Of course, I need hardly say I believe absolutely in the single-phase transmission. But I agree with Mr. Sprague that forever the direct-current motor will be superior to the alternating, and I represent both of these ideas in combination. Reliability, which he has emphasized, is, I agree with him, of the utmost importance; and in that connection I wish to point out that there probably is nothing electrically operated in the world in which reliability is of such great importance as the turrets on the battle-ships. No matter what the system might have in other regards in the way of advantages, if it were not absolutely reliable, or as nearly so as such things can be expected to be, it would have no chance whatever of being used. Reliability is the first factor in the control of those turrets.

Another point Mr. Sprague has commented on is one that I agree with him is of great importance, and that is the protection of the people in the train again the possibilities of danger from the high voltage, due to any kind of break-down or due to any leakage between the transmission circuit and the train circuit. And in that connection I wish to point out that the high-tension current on my system goes into the motor end of a motor-generator which is an entirely separate and distinct unit, that it is electrically and mechanically separate and insulated; and this is very different from a case in which the high-tension circuit is placed in as close proximity to the working circuit as the ordinary insulation of a static transformer would put it.

In the case of the Oerlikon Company installation, they employed a moving contact at the rail in addition to the overhead one, with the idea of insuring complete safety at that point in case any difficulty should arise as regards contact at the wheel, but the necessity of that may be open to debate. I am inclined to agree with Mr. Lamme,— that the higher the voltage the more certainty there will be that the contact will be preserved at the ground. Therefore, I think that the thing that needs to be protected most is the working circuit on the train, and that we ought to

keep that as separate as we can keep it, and not get it as close as we can, with only a thin layer of insulation between it and the transmission circuit of high pressure.

On one point I am quite at variance in my opinion with Mr. Sprague. He said he did not think the Pennsylvania Railway would during the life of most of us extend electric traction on its line beyond the New York tunnel plant. In that I cannot agree with him. I have nothing more than my faith in the future of electric traction systems to justify my opinion — I don't know any Pennsylvania Railway engineer's opinion on the subject. I am merely banking on electric energy and electric engineering.

Mr. Lamme has emphazed the importance of low voltage in the motors, but he made the error of saying that we could not have direct-current motors for railway traction without having rather high-tension in the secondary circuit. Of course, in my system while securing the advantages of high-tension transmission the advantages of the low voltage in the motor circuit can be fully realized.

On the subject of electrolysis, I agree with Mr. Lamme. It is one of great importance and is going to cut a great figure in electric-railway work in the future, and of course in that regard my system has the advantages that are common to all alternating systems.

Referring to what Mr. Scott said about the crawling motor, and how if he wanted the motor to crawl he would use my system, but if he wanted full speed in addition to crawling he would use the three-phase motor. I want to say that the General Electric has three-phase currents and motors at their command and are no doubt as competent to handle them as are engineers abroad. In large central stations, in which one of the most important points is to have a *coal* hoist which will hoist the coal reliably night and day, they do not use the three-phase current, which could be used for such purposes, and which I should judge from Mr. Scott's remarks he would consider eminently suitable and superior to my system; but, on the contrary, with the three-phase currents right there, they do install a motor generator and my system for driving the hoist, because it does give superiority of control and reliability in service.

CHAIRMAN DUNCAN: May I ask that discussions be limited to ten minutes, please.

MR. B. J. ARNOLD: I am going to try and avoid saying anything about my own system this morning — not that I am ashamed of it, because I am very proud of what has been done with it as a pioneer in single-phase work, regardless of its merits. I do not know what my friend Sprague said before I came in, but I do not know that if it were not for the fact that he remains young so long in appearance I would say that his ideas of late years are quite what we might attribute to a gray-headed man — but he has not turned gray fast enough to justify it. But I do know that the atmosphere he has been in the last two or three years has put a certain conservatism into him which is very admirable, but we cannot get him away from the direct-current system quite as rapidly as I had hoped. However, he has maintained a consistent position on the matter and

presents the merits of the single-phase as strongly as he feels they can now be advocated.

Mr. Lamme's point on the low voltage question I can see nothing in because I do not see but that we are getting along very well with 500 volts with direct motors, even 600 or 700 volts, and I have seen no difficulty in using alternate-current motors working at as high pressures. I think his position must be due to the fact that there is some other reason for using low voltage, due probably to the method of control or something else which he has not made clear. I am not able in the time at my disposal to bring out all the technical points involved, but I cannot see anything in the argument, and there is a certain disadvantage to it with the systems that are in use, because you must make and break this low voltage current, which is objectionable. There are certain elements both ways: You can make and break too high; you can make and break too low voltage.

I am going to call on Dr. Steinmetz to bring out some other points after I get through. The point made by Mr. Scott about the fact that it is a real advantage to the train despatcher to have railroad trains that run at a certain rate of speed and cannot run any faster, I think that is a very poor railroad, and if we had an association of train dispatchers here I think they could answer the argument much better than I can. It seems absurd to me to say that we do not want railroad trains to run high speeds, when we do want it because there are necessities for it.

Mr. SCOTT: You misunderstood me, sir.

Mr. ARNOLD: I do not mean to misrepresent you.

Mr. SCOTT: I said a certain railroad had its rolling stock equipped for certain speeds.

Mr. ARNOLD: That is what I said, and I do not misrepresent you. I understand you to say you thought it desirable to have a constant speed.

Mr. SCOTT: If there were people that wanted their rolling stock for certain speed, and wanted to run it higher of course they would not —

Mr. ARNOLD: In my judgment that is impractical railroading; however, I am only one individual.

I am a great believer in as much simplicity as you can yet, in spite of the fact that I have adopted complicated means to arrive at simplicity. But the system which will win is the most simple one and the one which costs the least money. And no matter what our present ideas are as to the merits of the various systems, that is the thing that will finally decide the question. And, therefore, I maintain that the two wires overhead and three-phase system are impractical for railroad work. We have got to have a single conductor, and if we could eliminate the conductor entirely we would be as nearly perfect as possible.

The other point is we have got to have pretty high voltage on our working conductor due to inductive loss in the rail. I have experimented with voltage as high as 6000 on the working conductor — and haven't killed any one yet, and hope not to. It has been tried by the parties I represent, as you know, as high as 15,000 volts, and I think it was tried in Mr. Leonard's locomotive, which so far as I can learn, has worked fairly successfully, and it seems to me the nearest approach to

perfection of means for getting the energy on the train. Mr. Chairman, I am going to stop. I think I have used up my ten minutes.

Mr. Henry Pikler: Permit me to say a few words concerning this subject. I want to refer particularly to Mr. Steinmetz' discussion. Mr. Steinmetz gave us a very clear and concise description of the characteristics of the different alternating-current motor systems, and pointed out the advantages of one motor system above the other in the railroad service. The conclusions, however, which Mr. Steinmetz has arrived at I do not quite agree with. Mr. Steinmetz treated the polyphase induction motor rather step-motherly, and I think he called it an unsuccessful attempt. From this statement it appears that Mr. Steinmetz does not want to recognize the fact that such railroad systems are in a very satisfactory condition of operation. I refer especially to the Valtellina three-phase railroad, designed by the Ganz Company of Budapest, the experiments of the Siemens & Halske Company, and similar work of the Brown-Boveri Company. Of course, nobody will think of using polyphase induction motors for street-car service where stops are frequent. That disadvantage of the polyphase induction motor, that its torque decreases with the square of the proportional decrease of the impressed e.m.f., disappears when the central station and sub-stations are reasonably designed and equipped.

As to the variation in the speed for such railways, I think two variations — that is, the highest speed and the half speed — are entirely satisfactory. Half speed may be obtained either by concatenated operation of two motors or by changing the number of poles as has been done by the Brown-Boveri Company.

These, however, are general points in comparison with other motor systems, but if we would go into the details of design, performance and manufacture of the motors and the whole railroad equipment we find so many points in favor of the polyphase induction motor that it makes it much more desirable than any of the present systems for that purpose. The polyphase railway system of Valtellina Railway in Italy was so satisfactory in service that the Italian company accepted the entire equipment before the expiration of the test period. Discussion or hasty experiments will not prove the advantage or disadvantage of one system or the other, the future and long service in actual operation will effect the natural selection of the best system.

Mr. A. H. Armstrong: I want to give two or three historical facts connected with three-phase motor work in this country. The General Electric Company has had, from time to time, a large number of problems submitted to it in connection with railway work upon which they were supposed to pass their best judgment in regard to motive power. Some of those problems were so extensive and called for such peculiar treatment that the direct-current motor failed to serve the purpose in every case and some form of alternate motor was necessary. Up to within the last year or two, the three-phase induction motor was the only type that could be considered, and we have unsuccessfully tried for the past ten years to adapt a constant-speed limited-output three-phase motor to railway conditions.

The chief objection to its use has been its constant speed characteristic, which would make the locomotive or car attempt to go up a ten per cent grade at the same speed at which it operated on a level,—the restricted output of the motors themselves, which, together with their poor power-factor, made the system expensive to install and operate.

Most of our suburban railways have a very irregular profile, ranging from a level track to 4 or 5 per cent grade, and in such cases the motive power must be designed to haul the car or train on the maximum grade, and still operate efficiently on level track. A 5 per cent grade will require a tractive effort of 110 lbs. per ton or more, while a level track will require twenty lbs. or more; thus the motor may be called upon to deliver five or six times its normal torque when operating on maximum grade. Furthermore, the torque of the induction motor varies as the square of the line potential, and must have sufficient margin to take care of the fluctuations in trolley potential which will occur in a commercial railway system. Giving due recognition to the fact, further, that the motor and distributing system all operate at a poor power-factor, it becomes necessary under the conditions of commercial operation to design the induction motor for such a large maximum torque that it will operate normally at a small percentage of its maximum output, with consequent poor constants.

The variable-speed motor, of which the commutator motor is the best type, is especially adapted to railway work, because it embodies most of the characteristics wherein the three-phase motor is deficient. It is a variable-speed motor, and follows the footsteps of the direct-current motor, which has proved itself well able to take care of general traction problems. Its output is unlimited, in a railway sense; that is, the motor can slip its wheels, which is all that is required; and its general speed characteristics, being of a variable-speed nature, are well adapted to the fundamental requirements, not only of suburban, but also of main-line high-speed railways.

I believe that the company which I represent have been justified in passing over the three-phase motor as not being adapted to general railway conditions, and were wise in waiting until a motor had been developed which embodied more of the good characteristics of the direct-current series motor.

Mr. B. G. Lamme: I wish to add something to Mr. Leonard's remarks in regard to the Swedish railway problem. Mr. Dahlander, the Swedish engineer mentioned by Mr. Leonard, made a report to the Swedish government on the question of electrification of the Swedish railways, and in this report, if my memory serves me right, the system which showed the least cost was the Westinghouse single-phase system, but it was considered to new and untried to be recommended. That was about two years ago. Since that time Mr. Dahlander visited this country, and among other places he visited the Westinghouse works at East Pittsburg and saw the Westinghouse system in operation. He evidently reported favorably on his return to Sweden, for since that time an electric locomotive has been ordered from the Westinghouse Company by the Swedish Government. This locomotive is to be equipped with single-

phase motors of a frequency of twenty-five cycles per second, with a maximum voltage of 18,000 volts on the trolley line. The conditions are so arranged that different voltages can be tried on the trolley, with the maximum stated above. It is, therefore, evident that all of the European engineers do not favor the motor-generator locomotive system, as this order was placed after an investigation of all various systems proposed by the different companies. It may be noted that the Swedish Government has also placed orders with certain other companies for trial equipments, and in all cases these equipments comprise single-phase alternating-current commutator-type motors.

It has been suggested by Mr. Arnold that we did not adopt low voltage on the alternating-current motors in order to avoid danger of grounds, but that this voltage was used for other reasons. It was not my intention to give the impression that the voltages of 200 to 250 were chosen for this particular reason, but such voltages being fixed by features of design, there were compensating advantages. I intended to bring out that the motors being wound for 250 volts instead of 500 volts, our insulation stresses would necessarily be less than on the direct current.

Another point, which has not been brought out to any great extent, is the rail loss with alternating currents. In this country practically all rail work is being done at twenty-five cycles, and even at this low frequency, the rail loss is high. In some cases we have found it to be about four times as great as with corresponding direct current, while in other cases it was even higher. This means, of course, that relatively high alternating-current voltages are used on the trolley, or the alternating current should be fed into the track at more frequent intervals if high voltage is not used. Another way to reduce this loss will be by the adoption of lower frequency such as fifteen to twenty cycles per second, as is done on some of the European polyphase roads. This may be an important factor in fixing the frequency when it comes to equipping the large railroads electrically.

In connection with the European polyphase roads, I will mention that I visited a number of these some time ago, and the ones I saw were operated successfully in the sense that they were doing what they were planned to do. These roads did not possess the flexibility of operation that we are accustomed to in this country, and I was forced to the conclusion at the time that the reason they were considered successful was because there were no corresponding direct-current systems in the immediate neighborhood to furnish a comparison.

Mr. E. K. Scott: Two companies in Italy are running two lines.

Mr. Lamme: I did not see those lines.

Mr. E. K. Scott: The governments are preparing the statistics and have been doing so within the last year. They are within a few miles of each other.

Mr. Lamme: I did not see the Valtellina line. The data which we have prepared on the polyphase railway system in this country indicate that where polyphase motors are used for frequent starting and acceleration, they could not compare favorably with the direct-current system, even when arranged with the "tandem" or "concatenated" control. That fact was brought out I believe two or three years ago in a number of papers before the American Institute of Electrical Engineers.

Similar data has shown that the single-phase alternating-current system with frequent starting and acceleration is superior to the direct current in efficiency. The single-phase system is, therefore, superior to the direct-current system under the very conditions where the direct current is far superior to the polyphase system.

Mr. P. M. Lincoln: This matter of additional losses in the rails due to alternate currents has been cited as a very serious objection to the alternate-current system. I would like to say, however, in that connection I have figured over a good many different cases where alternate currents have been proposed, and compared the same with direct current. Under normal conditions, the alternate current with a thousand-volt trolley invariably gives a lesser loss in the rails than does the direct current at 500 volts,— due first to the considerably decreased current that the rail carries on account of the higher trolley voltage; and, second, to the closer supplying of sub-stations which can be allowed with alternate currents over direct.

A Member: You mean energy loss?

Mr. Lincoln: The energy loss is much less in the rail in the alternate current of 1000 volts than it is with 500 volts with the direct current.

Dr. Steinmetz: Gentlemen, the position which I take regarding the polyphase induction motor is not that such motors are not operative on railroads, but that the single-phase commutator motor is far superior, and the existence of polyphase railways shows that where you cannot use anything else, or believe you have nothing else, it can be made to work, after a fashion. It is not that we have not tried the polyphase induction railway motor in this country: since more than ten years we have been very energetically working on the polyphase induction railway motor, until we finally dropped it, only a couple of years ago, as hopelessly inferior for the general requirements of railroading, to the rotary-converter system with direct-current motors, and to the single-phase commutator motor. We have never built any induction motor railroad, though we have been hunting hard for a chance to do so, and were willing to build it without profit, but our engineers have really never been able to honestly recommend a customer to install induction motors, but even where conditions looked very favorable, closer investigation threw the balance decidedly in favor of the rotary converter system with direct-current motors.

Now, the rotary converter, which here in the States has been standard apparatus for ten years, is familiar to everybody, and known to be absolutely reliable, was practically unknown abroad until it was introduced from here, and is still viewed by some engineers abroad with some suspicion. Hence the necessity abroad, to make the induction motor go on railway cars, while here the converter permitted direct-current supply over unlimited distance, and, therefore, the question was not whether the induction motor can be used on railways, but whether it offers any advantage over the direct-current motor and converter system, and this question was answered decidedly in the negative.

The polyphase induction motor is a very beautiful apparatus when run at constant speed. But you cannot run it at more than one speed. It is possible to get half speed by concatenation, and, if anybody, I should

be prejudiced in favor of this because I invented this method here in the United States. Mr. Görges simultaneously invented it abroad. Unfortunately, in concatenation the first motor carries the exciting current of both motors, and when using the very small air-gaps customary in induction motors, or the still smaller air-gaps our European friends use, the constants of the motor chain may still, if not good, at least not be hopelessly bad, especially at low frequency. But I have never been able to get a practical electric railway engineer even to consider such small air-gaps, and with the very smallest air-gaps mechanically permissible in railway motors, and the great limitations in space, especially in diameter, of railway motors, the constants of the motors in concatenation (or cascade connection) are usually hopelessly bad, so much so that two motors in concatenation may consume more current than both motors consume when giving the same torque in parallel connection. That cuts out this arrangement from further consideration.

The induction motor is well suited where you desire to go at a constant speed and load. This may be the case with a very high speed railway, where the torque required when running at full speed is of the magnitude of the starting torque. Then the question may be taken up again, but not under ordinary railway conditions.

Three-phase requires two wires, which is a nuisance and which is unendurable in a large railroad yard — where one wire or live rail is just one too many.

I desire to say one word regarding my friend Mr. Leonard. I can fully corroborate his statements on the beautiful control of speed and power given by his system. You are able thereby to start with powerful torque to run at any desired speed, run very slowly at constant speed, stop exactly where you desire to stop — in short, get a most beautiful control. And that is the reason why his system is used for the turrets of battle-ships, and to a certain extent in high-grade elevators.

But that is not the problem of the electric railway. What we want from the railway motor is to get away as quickly as possible, to run efficiently at high speed and at half speed. It is not necessary to run at any and every speed continuously. But what we want of the railway motor is to be as simple as possible; that is, to do the work with the least possible apparatus.

As regards efficiency of operation, if we look at the characteristics of the single-phase commutator motor, we will find that the whole range, from stand-still to full speed, is about one-quarter to one-sixteenth, in which, with rheostatic control, a resistance is used in the motor circuits, the rest is running on the motor curve; that is, at the highest possible efficiency, so that even in a service requiring very frequent starting, if we investigate the amount of power which could be saved by motor-generator control, it is so insignificant as not to warrant the complication. But from three-fourths to fifteen-sixteenths of the speed range, or during by far the greatest part of the time, Mr. Leonard's method must be decidedly inferior in efficiency, due to the constant losses in the motor-generator set (even if a very high-speed set), which a direct operation of the motor saves.

As regards the statement relating to the conservatism of large companies, I do not think I need to discuss that; but it is possible that a conference of impartial expert engineers does not always look at an invention quite as favorably as does the inventor himself.

To return to the railway induction motor, I had quite a considerable and variegated experience with it, and no doubt so did others. The first complete car equipment with two three-phase induction motors was in operation on the experimental track of the General Electric Company in 1894. It came to grief by our experimenting on a very short track which was used also by freight cars, in trying to show the powerful torque obtained by the motor brake, on reversing the motors. I believe my friend Armstrong was at the controller. Unfortunately one of the two trolleys came off, and the motor ran single-phase, without our knowing it (by the way, another early claim for single-phase railway operation), and a freight car happened to be a very short distance in front of our motor car — and you know what happens when an irresistible force meets an immovable body. Since then we have built several more equipments, but, as I stated before, we never have felt justified in recommending three-phase induction motors for railways.

Mr. F. J. Sprague: My friend Mr. Arnold — for whom no one has a higher affection than myself — would seemingly put me in the position of an opponent of the alternating-current motor, and suggests lack of virility for having enlisted too heatedly in the ranks of conservatism. As to this last, I am reminded that he has agreed with me on all the salient points of the New York Central equipment, and that we have a very harmonious board. The five gentlemen composing it have fought out their difficulties over the table, and come to a common conclusion, on which I, for one, am quite willing to stand.

So far as high potential is concerned, I am fully aware of all the economic facts achieved by its use, and I have been advocating it a good many years, starting with 600 volts in 1886. There is no one who has less antagonism than I to the development to perfection of the single-phase alternating-current motor, or any other. As engineers we hope to see it, and there are no men who will more completely welcome the perfect result after the diseases of the machine have been cured.

As to virility, it is possible that age, gray hairs and wrinkles are coming upon me, but if so they may tell of a good deal of hard work in the past twenty years, but I am still quite ready to assume any responsibility required by an engineer within the limits of technical risk and pocketbook. My gorge rose a bit when Mr. Leonard spoke of the multiple-unit system. For a long time I have been trying to hammer the definition of "multiple unit" into the electrical dictionary. It is not, as Mr. Leonard indicated, and as some of my other friends have described it, simply an assemblage of motors on different cars under common control. That is not necessarily a multiple-unit system — and I must beg to be allowed to speak authoritatively as to that, because, ungrammatical as the term is, I happened to be the one to coin it, and to use it for a specific purpose. It is simply intended to define a system of a plural control of a

plurality of controllers by which a number of units can be assembled into a train, each unit being absolutely complete without any dependence upon or relation to any other except so far as relates to control of the several main controllers; the propelling motors, main controllers and collectors are all individual to the car on which they are situated. When the units are put together, and through a secondary system they are controlled and operated from one or more points, then and there only do we have multiple-unit control.

The distinction between the systems mentioned by Mr. Leonard and others and the multiple-unit system is that there are no heavy currents passing from car to car in the latter. The only currents passing, except where shoes are connected together for the purpose of preventing sparking on icy and sleety rails, are control currents, and these are of magnitude too small to consider. Mr. Lamme, since he refers to current transmission, must have missed my point when I said that the continuous-current motor was a better one than the alternate-current motor. I said that, considered only as a motor, in the matter of weight, efficiency, reliability, ease of construction, and reduction of liability to damage when working in the ordinary way, the continuous-current motor is the superior. The fact is the present effort is to make a series motor run on alternating-current circuits, and to utilize all the existing advantages, while getting rid of some inherent difficulties which crop up.

Again Mr. Lamme, or some one, took exception to the question of danger that might arise. I do not care to what potential you go, there is a period, fifty times a second, where you pass zero. If at that time the car is on a bad rail and making poor contact, and there is a leak on the high-tension connection, it may be possible for a person boarding the car from moist earth to get a severe shock.

To break through and make contact from wheel to rail there must certainly be a rise of tension from zero to some point which is necessarily sometimes higher than might exist with a rail arc when using continuous current. I do not wish to speak as an alarmist, or say that these difficulties will not be overcome, but it is folly to ignore them, and we must recognize the defects of any system which is being considered. My criticism is we are apt to brush aside what has been done in the past, and promise too much for a new departure, because it fulfills certain conditions, and that we ought not to do.

Dr. STEINMETZ: What especially impresses me is that induction-motor railways have been run seven or eight years ago; the commutator motor has been brought out only within the very last year or two. But the amount of interest which the alternating commutator motor has raised, the great activity displayed in all countries, compared with the very low activity in the induction motor, give me the general impression that the commutator motor appeals to the railway engineers as greatly superior.

CHAIRMAN DUNCAN: Our time is exhausted, and as Mr. Arnold started the discussion I will ask him to close it.

Mr. Arnold: I think it is pretty thoroughly closed now. We have pretty well covered the theory. I am glad to see the sentiment in favor of the single-phase motor, regardless of what it has done in the past. I am bending my energies to it, and I think with what we may all do, we will have great results to report.

TRANSMISSION AND DISTRIBUTING PROBLEMS PECULIAR TO THE SINGLE-PHASE RAILWAY.

BY PAUL M. LINCOLN.

Up to the present time practically all long distance power transmission has been carried on with three-phase currents on account of the obvious advantages due to its use. The use of single-phase currents, however, introduces practically no new elements into the transmission problem. Its effect is to simplify the arrangements both of the line and the translating apparatus at the ends of the line. On the line two conductors instead of three will be used with a corresponding reduction in the number of insulators. At the terminals one transformer will take the place of a group of three and the switching apparatus is very greatly simplified.

One apparent handicap under which the single-phase line labors is the apparent fact that to transmit a given amount of power a given distance with a given loss requires more copper single-phase than three-phase in the ratio of 4 to 3. If we assume that the voltage between the single-phase terminals is equal to that between any two of the three-phase terminals, this apparent fact holds. Under normal conditions of operation, however, this assumption is not fair to the single-phase line. It is evident that so far as the transmission line is concerned, the true criterion of voltage strain is that which exists between any conductor and ground and not the voltage between conductors. It is further evident that under normal conditions ground potential will exist at the geometric center of the electric system. For instance, ground potential for the single-phase line will exist at a point midway between the terminals as shown at (*a*) Fig. 1, while in the three-phase system it will exist at the geometric center of the triangle as shown at (*b*). With the same terminal voltage, therefore, the insulation strain between any terminal and ground will be the greater in the three-phase system in the ratio of 2 to $\sqrt{3}$. But if the terminal voltage be so adjusted that the insulation strains to

ground be made the same, then to transmit a given amount of power a given distance at a given loss will require for the single-phase line an amount of copper no greater than that required by the three-phase line. In other words, for equal insulation strains on the line the terminal voltage of the single-phase system may be greater than that of the three-phase system in the ratio of 2 to $\sqrt{3}$.

It may be well to draw attention to the fact that the above observation holds good only for the normal condition, that is, the condition that ground potential occurs at the geometrical center of the system. If one of the conductors becomes grounded an abnormal condition arises and the insulation strain becomes equal

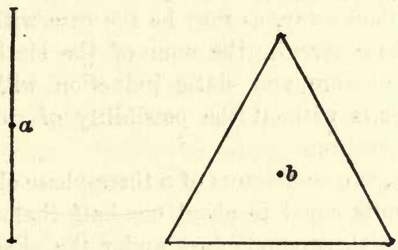


FIG. 1.

to the terminal voltage. Under this condition, however, the three-phase system suffers the disadvantage of having the insulation on two conductors subjected to a strain equal to terminal voltage, while in the single-phase system only one conductor is so subjected.

On account of the fact that a polyphase generator is for a given output much lighter and cheaper than a single-phase generator, it becomes of advantage, so far as the generating plant is concerned, to derive the single-phase currents necessary for operating a single-phase railway from polyphase generators. The saving in cost of generators thus effected amounts to approximately 30 per cent. In order to secure this advantage it is necessary to use a switchboard and transformer equipment which is somewhat more complicated and expensive than would be the case with single-phase generators, but as a rule not sufficiently so to prevent a greater economy in the use of polyphase generators over single-phase. For this purpose the two-phase generator is in general preferable to the three-phase since it is easier generally speaking to divide a given amount of single-phase load into two parts than

into three parts. Three-phase generators can, of course, be used but a balanced condition of load is obviously more difficult to secure.

The use of single-phase current from two wires of a three-phase line also involves a tendency to produce disturbances in neighboring telephone and other circuits, which is not apparent at first thought. Under the normal condition of operation of a three-phase circuit the sum of the static potentials of the three phases is always zero at any and every instant of time. Therefore, static induction on neighboring wires is due only to the fact that different distances necessarily exist between the disturbed circuit and each conductor of the three-phase circuit, and, therefore, is matter which can be corrected by proper transpositions. If, however, one of the three wires be taken away, as may be the case with a single-phase from a three-phase circuit, the sum of the static potentials no longer remains at zero and static induction will take place on neighboring circuits without the possibility of correction by any method of transposition.

In other words, two conductors of a three-phase circuit will under neighboring circuits equal to about one-half that which would be occasioned by the three conductors under the abnormal condition arising when one of them becomes grounded. Therefore, if there is any danger of disturbing neighboring circuits by static induction, it is advisable on this account to use three distinct two-conductor circuits rather than the alternative of taking single-phase from the three conductors of a three-phase circuit. An alternative is to carry all three of the conductors to all points to be served. This often involves running three wires where two would carry the load simply for the purpose of obtaining the static influence due to this third wire. Since the static influence is independent of the material of the wire and also largely independent of the size of the wire, this third conductor need not necessarily be as expensive in first cost as the other two constituting the working circuit.

In general, therefore, the transmission problem is changed but little by the adoption of single-phase in the place of three-phase. But when we come to the problem of the distribution of alternating current to cars on trains along the line of a railway we find a material difference between this and its counterpart, the distribution of direct current to railways. In the following discussion

it is assumed that the general arrangement of the typical alternating-current railway will be practically the same that is now followed in the typical direct-current railway. That is, the system will consist of a generating station sending out the required energy at a high voltage. At various points along the line this high-voltage energy will be transformed down to the voltage that has been selected as the trolley voltage and fed directly into the trolley. The general arrangement of the alternating and direct-current systems is, therefore, very similar. The main differences between the two systems are, first, the elimination of a trolley voltage limit except that set by considerations of insulation and safety; and second, the elimination of rotary converters from the sub-stations and the consequent elimination for the necessity of constant attendance.

Assuming that in any given case the trolley voltage is fixed, there will still remain two variables to be determined, first, the cross-section of the trolley copper, and second, the distance between transforming stations. These two quantities are evidently interdependent. That is, a variation in one requires, in order to render a given service, a variation in the other. For instance, if we increase the number of feeding points the cross-section of copper to convey a given amount of power with a given loss is decreased.

The considerations upon which these quantities should be determined may evidently be classed under the following heads:

1. Maximum economy.
2. Voltage drop.
3. Insurance against accident.
4. Mechanical considerations.
5. Avoidance of undue multiplicity of stations.

1. Maximum Economy.

It is evident that a cross-section of copper and a distance between transforming stations should be used which will give the maximum economy, provided the limit as thus set does not fall beyond that as absolutely fixed by other considerations. Kelvin's law gives us a basis for the calculation of the most economical cross-section of copper. As is well known, this cross-section is dependent only on the cost of power, the cost of conductors in place, the load factor and the interest and depreciation on the investment for conductors. Knowing the above factors, we may

derive at once the density of current per unit of cross-section of copper which will be most economical. This current density per unit of cross-section is entirely independent of the distance power is to be transmitted as well as the amount of power and the transmitting voltage. Once having derived the most economical density of current per sq. in., it is easy by making certain other assumptions to fix the most economical distance between transforming stations as well as the proper size of copper. The most economical distance between stations is given by the following formula:

$$D = .00314 \sqrt{\frac{KVA}{WP}}$$

in which

D = distance between adjacent transforming station in miles.

K = the cost of a single transforming station in dollars.

V = trolley voltage.

A = most economical current density in amperes per sq. in. as derived from the conditions mentioned above.

W = average apparent kilowatts used per mile of road.

P = price of copper in cents per pound.

This formula is simply another method of saying that to make first cost a minimum the cost of the transforming stations should be made equal to the cost of the trolley copper. Knowing the values of A, D and W the cross-section (in circular mils) of the trolley is, of course, fixed by the expression

$$cm = \frac{6.35 \times 10^8 DW.}{VA}$$

To derive the above expression for distance between stations the assumption is made that the cost of a transforming station is independent of its capacity, an assumption which of course is not strictly true, but one which is not so far from the truth as appears at first sight. The total cost of a transforming station is made up of transformers, auxiliary apparatus and building. The cost of the building and the auxiliary apparatus will remain practically stationary for large variations of capacity. The cost of the transformer item, of course, decreases with decreased capacity, but decrement in cost is not nearly so great as the decrement in capacity. Further, the decrement in capacity to render a given

service will be less than the decrement in distance between stations. For when a car or train is opposite a given transformer station practically all of the energy to operate it must come from that transformer station. Within wide limits too the maximum load on any transformer station will be that due to a single car or train. The maximum load on any transformer station is, therefore, within wide limits, independent of its spacing, and, therefore, independent of its capacity. Closer spacing only limits the element time during which the load pulls on a transformer station, and not the element of maximum load. Since the capacity of a transformer station should be adjusted to the root mean square load and not to the average load, it follows as stated above that the decrement of capacity in transformer stations is not proportional to the decrement of spacing.

As indicated above, however, the consideration of economy should be allowed to fix these quantities only when they fall within the limits as fixed by other considerations.

2. Voltage Drop.

It is of course essential that sufficient voltage exists at the car to operate it and it is preferable that the fluctuation of voltage be within the limit of successful incandescent lighting; and in the spacing of transformer stations and the choice of trolley wire the dictation of economy may have to be modified by the dictation of allowable drop. In comparing the question of voltage drops in an alternating-current railway line with those of a direct-current railway line, two marked differences obtain, one an advantage to the alternating system of distribution and one a disadvantage. An advantage for the alternating system accrues from the general fact that alternating voltages are capable of being transformed with comparative ease and high efficiency. It is possible, therefore, to install an apparatus on an alternating-current car whereby any voltage drop that occurs may be compensated for.

On the other hand, the alternating system labors under the disadvantage that inductive drops which are peculiar to the alternating system are added to the ohmic drop which is the only element to be considered in the direct-current system. The amount by which the total drop is increased by this inductive effect is dependent of course upon the size of trolley wire, its distance from its return, the nature of the return, the frequency and the power

factor of the load. The general statement may be made, however, that with 25 cycles, the usual height of trolley wire, the usual power factors that will be met in practice and sizes of trolley wire not exceeding No. 4 — the total drop in the trolley line will rarely be more than the ohmic drop increased by 50 per cent. This figure assumes that the term "ohmic drop" takes into consideration the additional loss that alternating current causes in the return rail circuit over that caused by direct current.

3. Insurance.

A second point which should be borne in mind when determining the size of trolley and the distance between stations, and which may require a modification of these quantities as fixed by consideration of economy, is the possibility of the temporary breakdown of any transformer station. These elements should be so chosen that in this event operation of cars or trains past the disabled station may be effected from adjacent stations. This condition may fairly be considered as an abnormal one, however, and so long as operation under this condition still remains possible the questions of economy and drop may be lost sight of in that section where the abnormal condition exists. An arrangement of transformer stations which may be suggested in this connection is one in which a reasonable amount of spare capacity is provided by making each transformer station a certain percentage larger than necessary to take care of its normal load, and only providing a single transformer in a station. In case of the disablement of any station, its load can be taken care of by the adjacent stations until such time as the transformer can be replaced.

4. Mechanical Considerations.

This point is sufficiently covered by the consideration that the trolley wire must be on the one hand of sufficient size to make a strong mechanical structure, and on the other hand not of so large a cross-section as to make the supporting structure unduly heavy. The size dictated by maximum economy must, therefore, be subject to the modification of mechanical fitness.

5. Danger of Multiplicity of Stations.

In viewing this problem from the standpoint of the high-tension line it must be borne in mind that every point at which it is neces-

sary to tap the line and take power becomes a point of danger, a point where accidents may happen. And the higher the high-tension voltage the more difficult and expensive it becomes to take power from the line, and the greater becomes the liability of danger. This point becomes a good reason for reducing the number of transformer stations to a minimum.

It may be easily gathered from the above discussion that there is no golden rule for the determination of the spacing and capacity of transformer stations or the size of the conductor. It is, like most other engineering problems, a matter of compromise between various elements, some of which point in one direction and some in the other, and a matter which must be determined by engineering judgment rather than by any inflexible law.

PROTECTION AND CONTROL OF LARGE HIGH TENSION ALTERNATING-CURRENT DISTRIBUTION SYSTEMS.

BY GEORGE N. EASTMAN, *Delegate National Electric Light Association.*

The principal object to be attained in the installation of protective apparatus is continuity of service. While the precautions that are necessary to be taken in the operation of one system may differ materially from that of another, the protective apparatus installed to insure continuity of service would be substantially the same for either system. There is a wide difference of operating conditions in the present large high tension systems, due to the different types of apparatus which are installed. Contingencies which will frequently arise on one system will be infrequent on another. In treating the subject then, it is necessary to outline the general type of the system which is to be considered, principally in regard to the apparatus which it serves.

A system may have overhead and underground lines supplying step-down transformers operating induction motor generators, synchronous motor generators or rotary converters, or it may have induction motor generator sets or synchronous motor generator sets directly connected to the primary distribution system. The combination of nearly all these conditions is obtained in a few large high tension transmission systems now in operation in some of our large cities. It is evident that the contingencies which will arise on such a system will be more varied than the contingencies arising on a system supplying only one class of transmission lines and only one type of translating apparatus. The system of the Chicago Edison Company and the Commonwealth Electric Company is representative of the former class, and as examples and conditions presented throughout this paper will refer particularly to this system, a brief description of the principal features relative to the examples and conditions cited will be given.

The high tension system of the Chicago Edison Company and the Commonwealth Electric Company consists of a 3-wire, 3-phase, 25-cycle, 9000-volt primary distributing system fed with but one ex-

ception by three-phase star-wound generators. The system is operated from two generating plants, the Fisk Street station having at present a normal capacity of 15,000 kilowatts, and the Harrison Street station having a normal capacity of 10,000 kilowatts. The neutral of the 9000-volt generators is brought out and connected to a common ground bus in each station.

The primary distributing lines consist of 43 lines of three-conductor, paper insulated, lead covered cable and one overhead line interconnecting generator stations and sub-stations. With few exceptions, the cables are made up of No. 4-0 conductors with insulation of 6/32-in. paper concentric with the conductor and 4/32-in. paper wrapped over all, jute or hemp filler being used, and the whole treated with a resin oil. The length of underground cables connected to the system is 63 miles. The length of overhead lines, 9.4 miles.

The translating apparatus in the sub-stations consists of 9000-volt, 3-phase synchronous motors direct connected to 60-cycle generators; step-down static transformers operating rotary converters and step-down static transformers driving induction motors for operating exciter generators. A diagram of the high-tension system is shown in Fig. 1.

Grounds on the System.

In the process of installing an underground three-conductor cable, the insulation wrapped over all the conductors is more liable to injury than the insulation concentric with each conductor. Any mechanical injury to the insulation concentric to the conductor is generally confined to the insulation of one conductor and is seldom obtained on all three conductors at one point in the cable. A resultant breakdown in insulation due to mechanical injury is, therefore, more frequent between conductor and ground than between individual conductors. The effect of electrolysis is to produce the same result. As a general rule a small hole is first obtained in the lead which is nearer to one conductor than it is to the other two, and the moisture entering causes a breakdown to ground.

The effects of grounds should be studied, and an effort made to determine the resultant effect which will be produced by grounds in all conceivable cases, in order that proper precautions may be taken to limit the extent of injuries to the system.

On any alternating-current system, the relative potentials which

exist between any part of the system and ground will depend upon the distribution of the electrostatic capacity throughout the system. The insulation resistance is necessarily so high that its effect

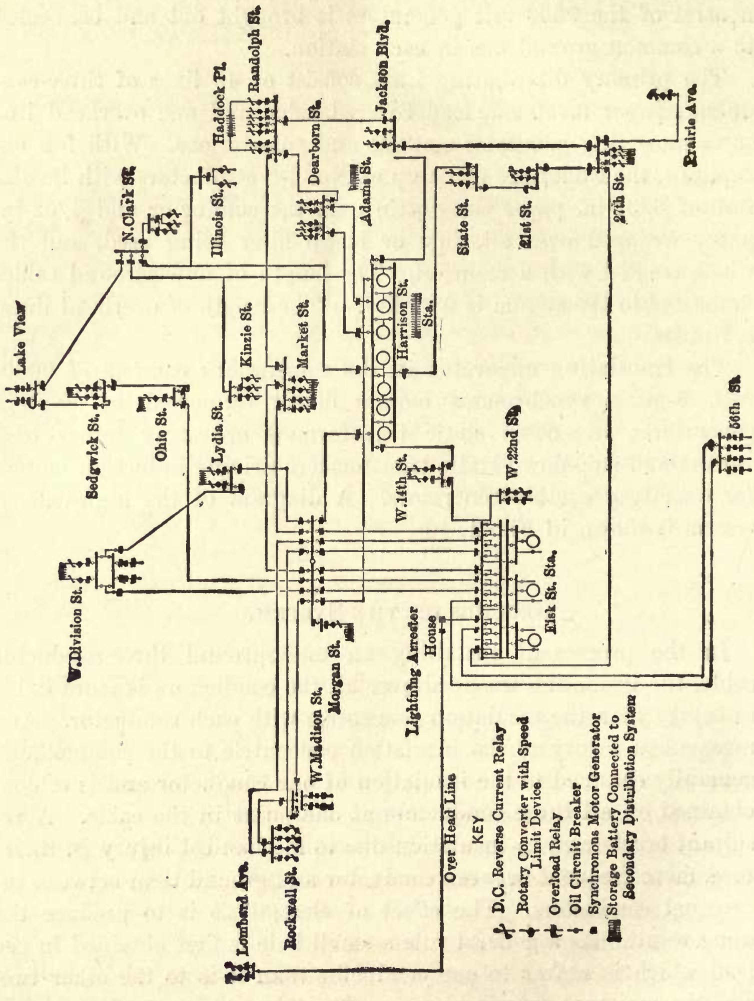


FIG. 1.

in determining the potentials which will exist between the system and ground will not be noticeable.

The condensance of the system performs the function of elastic ligaments, connecting the system to ground. The elastic limit of

the ligaments is the potential at which the dielectric is broken down and a direct short-circuit established. The effect of a ground on the system depends upon the nature of the ground and the value of its reactance in relation to the condenser reactance. An appreciation of the above statement can be best obtained by the presentation of a few examples which might occur in actual practice.

The total capacity of the overhead and underground transmission circuits of the Chicago system is 2.79 microfarads between two conductors, and 10.64 microfarads between each conductor and ground. The capacity reactance (condensance) between two conductors at 25 cycles equals 2285 ohms, and the condensance between each conductor and ground is 598 ohms.

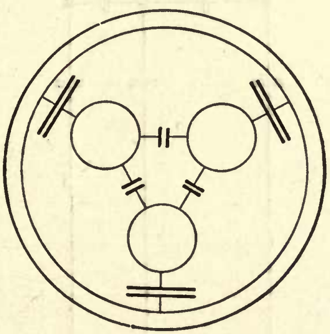


FIG. 2.

Fig. 2 represents the distribution of capacity in a three-conductor underground cable. The lines representing the condenser plates are drawn to scale so that a relative comparison between two conductors and between each conductor and ground is graphically represented. It will be noted that the capacity between conductor and ground which is the factor determining the relative potentials which will exist between ground and system is several times greater than the capacity between conductors.

The distribution of condensance in overhead lines is shown in Fig. 3. In this diagram it is assumed that the line conductors are properly transposed so that the capacity between conductors, considering the entire system, is balanced. It will again be noted that in the overhead system, the capacity between each conductor and ground is greater than the capacity between conductors.

It is interesting to make a comparison between the capacity of

a system with underground cables and the equivalence with overhead lines. If all the lines of the Chicago system were overhead, assuming a distance between conductors of 16 and 25 ins. respectively and a height of 35 ft. above ground, the total capacity of the system between two conductors would be .57 microfarads and between each conductor and ground .65 microfarads. The condensance at 25 cycles between two conductors would be 11,300 ohms and the condensance between conductors and ground 9620 ohms. The ratio of capacity in the overhead system to that in the underground system would be 1 to 16.4 between conductors and ground, and 1 to 4.9 between two conductors.

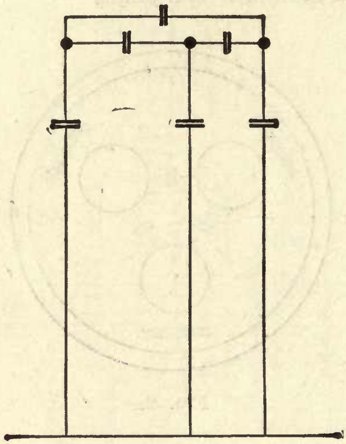


FIG. 3.

Diagram Figs. 4 and 5 represent the arrangement of capacity in relation to the three-phase pressure diagram. As in Fig. 2 and Fig. 3 the condenser plates are drawn to scale, so that a comparison can be made between underground system and an equivalent overhead system.

The effect of a ground on any conductor is to shunt the condensance of the system between that phase and ground, and it is evident that the relative potential which will exist between the system and ground will depend upon the nature and value of the grounding impedance and the relation it bears to the shunted condenser reactance.

An idea of the effect which will be produced by an inductive ground can best be obtained by an inspection of Fig. 6. In diagram

Fig. 6 it is assumed that the condensance of *C* phase is shunted by inductive reactance having no resistance component. It will be readily conceived that if the inductance is equal to the condensance, that the impedance of the circuit between *C* and *G* will be infinite, and the relative potential to ground will be determined by the capacity between the phases *A* and *B*. If these two condensers are of equivalent value, the ground will be located at the point G_1 midway between *A* and *B*, and the potential from *A* and *B* to ground will be one-half the delta potential of the system; the

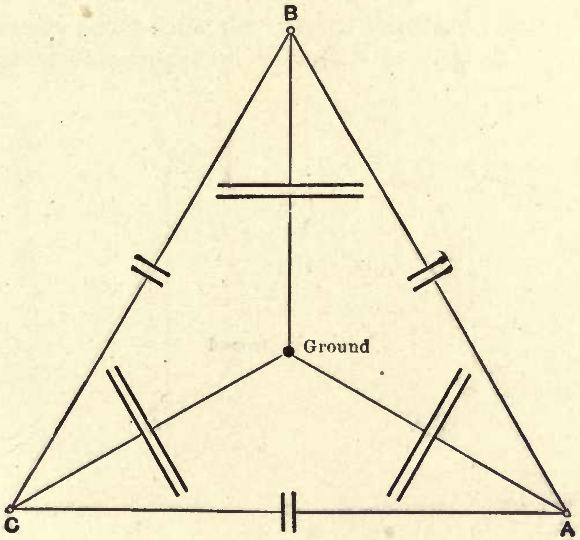


FIG. 4.

potential from *C* to ground will be 86.6 per cent of the delta potential of the system. As the inductance is decreased it will be evident that the potential between the system and ground will be increased; since the condensers between *A* and *B* are in series with an inductive reactance. The potential will increase as the inductance is decreased, until the latter is one-third of the reactance of each condenser. For this value of grounding reactance, the potential between system and ground will be infinite. With a further decrease in the inductive reactance, line $G\ G_2$ will swing through infinity and the potential will decrease along the line $G\ G_3$ until, when the grounding reactance is zero, *C* will be at ground potential.

If an inductive ground could be obtained having no ohmic com-

ponent, a ground of 199 ohms on the underground system of Chicago would produce an infinite voltage, and if the system were overhead, a ground of 3206 ohms would produce the same effect. Thus, it will be seen that the factor which determined the relative potential to ground depends both on the grounding impedance and the condensance of the system.

Fig. 7 is a diagram showing conditions which would be obtained when the ground is on the primary of one transformer of a star connected set of transformers. The transformer on which the

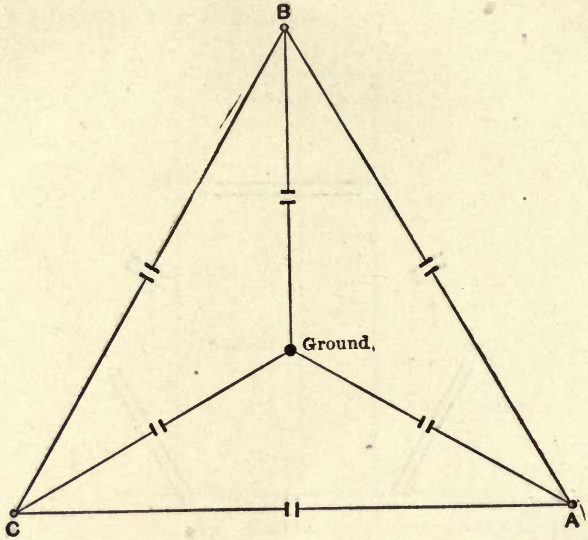


FIG. 5.

ground is obtained is connected between A and the neutral. The curve shown is plotted for a solid ground on the primary for different points along the winding. Condition m_2 would be obtained when the ground occurred in the center of the transformer. Condition m_4 would be obtained when the ground is on the primary, one-quarter the distance between A and the neutral. AL represents the pressure which would be impressed upon the transformer when the ground occurred at the center of the primary winding and CL and BL represent the potentials which would be impressed on the other two transformers.

Fig. 8 is a diagram of the same conditions, considering the system is overhead instead of underground. The results shown in

Fig. 7 and Fig. 8 are for transformers of 200-K.W. capacity each under full load conditions. It will be noted that a ground under the conditions given which would cause considerable trouble on an underground system would cause very little trouble on an equivalent overhead system. The same potentials would probably be obtained on an overhead system with transformers of about 20-K.W. capacity. Much higher potentials may be obtained if at the point where ground occurs an arc is produced.

Grounding the Neutral of Generators.

The remedy adopted for the Chicago system for eliminating the possibility of obtaining high potentials between the system and

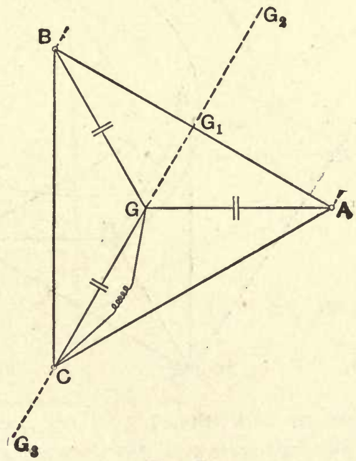


Fig. 6.

ground was the solid grounding of the neutral of all the star-wound generators in the generating stations. It is universally admitted that grounding the neutral will eliminate the chances of obtaining excessive electrostatic disturbances on the system. Fear is expressed by some engineers that with a grounded system, a ground on the system which directly becomes a short-circuit between neutral and one conductor of the generators will result in surging throughout the system, thereby producing results which would be as disastrous as the trouble which it was aimed to eliminate. In some instances a resistance has been installed between the neutral and ground to limit the flow of current to ground. It

is hoped that in this manner the short circuit could so be dampened, that surging would not result. In a large high-tension system it would be impracticable to install a resistance for the purpose of dampening short-circuit oscillations, on account of the enormous current which the resistance would have to take care of.

It would seem that a better system would be the operation of only one generator at a time with the neutral grounded, thus limiting the current which would flow on the occurrence of a ground to the short-circuiting current capacity of that machine.

It should be borne in mind that with the occurrence of a short-circuit which is limited to one conductor and ground, that the

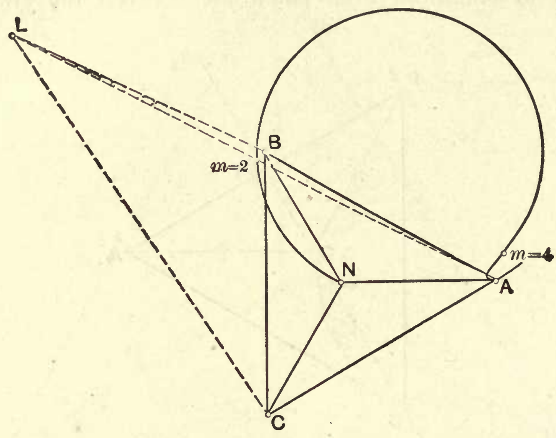


FIG. 7.

energy which is furnished the short-circuit will be supplied by the generators in the generating station and that the synchronous apparatus in the sub-stations, unless their neutrals be grounded also, will furnish no energy until the short-circuit has been translated to between conductors. Thus, if a ground can be detected and removed from the system before it has had time to develop into a short-circuit between conductors, the effect on the system will be greatly decreased. In the operation of the Chicago system, in nearly all cases the short circuits in the underground cable have occurred between conductor and ground, and when the overload relays were not retarded in their action by time limit devices, the circuits on which the trouble has occurred have been opened before the short-circuit was transmitted to other conductors.

GROUND DETECTORS.

The above fact has led to the investigation of a means for obtaining a ground detector which could be used for the purpose of indicating a ground or operating a relay controlling the circuit breaker of the circuit on which the ground occurs. For this purpose the Chicago Edison Company is experimenting with a device, a diagram of which is shown in Fig. 9. This device consists of a laminated iron ring having three independent windings of an equal number of turns, uniformly distributed over the core, and a fourth winding of any desired number of turns which is connected to a meter or relay for providing the desired indications. Each of the three similar windings is connected to the secondary of a line cur-

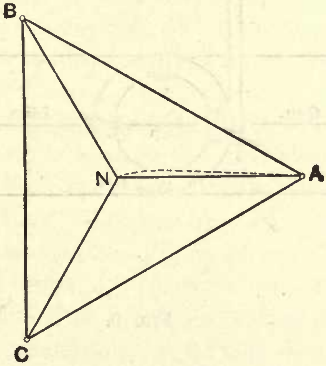


FIG. 8.

rent transformer. So long as there is no escape of line current from the line to ground the currents through the three windings will neutralize each other and no flux will result in the iron core. As soon as the ground is obtained part of the current fed through the transformer will return to the generator through the ground and an indication will be obtained by means of the fourth winding. It is hoped that by means of this with the combination of instantaneous and time limit relays, the line on which the ground occurs will be automatically located and its circuit breaker opened instantly. In this manner the ground may be cut off before the trouble has been transmitted to other conductors and the trouble limited to one line and only that part of the system which is affected by its operation.

OVERHEAD LINES ON CONNECTION WITH UNDERGROUND SYSTEM.

The introduction of an overhead line operating in multiple with a large system of cable introduces a very hazardous element and makes it necessary to safeguard the system against atmospheric charges. Every possible precaution should be taken with a view of preventing the transmission of a high potential on the overhead line to the underground system. There is but one overhead line connected to the Chicago system and although it has been in service only a few months several cases of trouble have occurred on it and

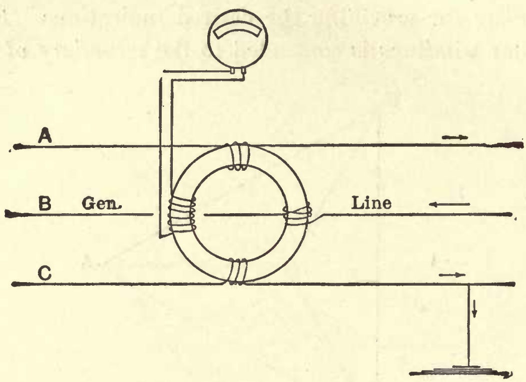


FIG. 9.

the protective apparatus installed has successfully prevented the transmission of trouble to the underground system. This overhead line is connected to the bus-bars at the Fisk Street station through a 900-ft. length of underground cable. At the junction of the underground cable and the overhead line, a lightning-arrester house was built in which were installed choke coils, lightning arresters and a circuit breaker on the line. The choke coils installed had an inductive equivalent of 200 ft. of overhead line. Two banks of lightning arrester were installed, one being connected to the center of the choke coils and the other on the overhead side of the coils. Besides the line circuit breaker in the lightning-arrester house, a circuit breaker was installed in the switchhouse. Care was taken to adjust the overhead relays so that in case of trouble on the line the switch in the lightning-arrester house would be the first to open.

Overload Relays.

One of the most important parts affecting the control of a high tension system is the overload relay which controls the automatic opening of the line circuit breakers. These relays should be capable of selecting the line on which trouble occurs and opening the line instantly. For this purpose a combination of a time limit and instantaneous element is necessary, the time limit feature being set to protect the cable or apparatus against dangerous overloads and the instantaneous device being adjusted to operate only in case of short-circuits or grounds. The time limit devices which have been used without the combination of these two elements have resulted in the operation of circuit breakers of lines on which no trouble has occurred, in some cases shutting down the entire system. In laying out the system, the application of the overload relay should be borne in mind and wherever possible the lay-out should be so arranged that each line receives its energy either over a number of lines, or else directly from the bus-bars of the generating station, in this manner causing the short-circuiting or grounding current in the line on which trouble occurs to exceed in amount the current of any other line on the system. To illustrate this point, referring to diagram Fig. 1 of the Chicago system, it will be observed that there are six lines connecting the Morgan Street sub-station to the Fisk Street generating station. In order to insure these lines remaining in service when a short-circuit occurs on lines connected beyond the Morgan Street sub-station, it will be necessary to set the instantaneous device on the overload relays for current values so high that the sum of the currents in all the lines is in excess of the short-circuiting current which the Fisk Street station is capable of delivering. The time limit element may be set low enough to protect the cable against the continuous overloads which would endanger apparatus and affect the normal operation of the system.

Oil Circuit Breakers.

The application of no other device has played such an important part in making the operation of a large high-tension system possible, as has that of the oil switch. Experiments have shown that with the presence of electrostatic capacity the open arc in air has very destructive effects. Instances have been obtained where, upon opening the circuit in air, arc lengths of from 20 ft. to 30 ft.

have been obtained. Confining the arc in oil, the phenomenon which is obtained with the open arc apparently ceases to exist. This fact should be borne in mind and precaution taken throughout the system as far as possible to limit to a confined space the short-circuiting arcs which are apt to occur. Every precaution should be taken with auxiliary circuits and devices upon which the operation of the circuit breaker depends. The opening of a switch or the falling back of a switch into a closed position may result in as much damage to the system as the most severe short-circuit. The switch should be capable of successful operation through a very wide range in voltage, in order that the control will not become inoperative when trouble on the circuits causes a drop in pressure of the secondary system.

Protection of Translating Apparatus.

The apparatus in the sub-station feeding from the primary distribution system should be protected with overload relays operating circuit breakers, both on the primary and secondary system. With a sudden reversal of current in either a series or a shunt-wound rotary converter the field is apt to be weakened to an extent such that a dangerous speed would be obtained. To prevent this, a speed limit device controlling the direct-current circuit breaker should be installed. To guard against the speeding up of a rotary converter on which the speed limit device has failed to operate and translating its excessive speed to other synchronous machines in multiple with it, the speed limit device should also control the operation of the alternating-current circuit breakers.

To reduce the liability of obtaining excessive speeds on converters, the sub-station translating apparatus should be arranged, wherever possible, so that rotary converters do not operate in multiple with synchronous motor-generator sets connected to the same line. The opening of the line switch in such a case would result in the dropping out of step of the motor, thereby causing the speeding up of the rotary converter due to the demagnetizing action of the heavy lagging current set up in the rotary armature.

In any system care should be taken to prevent the manual operation from interfering with the automatic. The combination of hand and automatic operated devices should be avoided as far as possible, thus minimizing the tendency of the operators to rely upon automatic devices. For example, when

certain cases of trouble arise the automatic devices may be deprived of their means of automatic control and hence fail to perform their functions of protection. In such a case an attempt to operate these devices manually would also result in failure and a loss in time which may cause the wrecking of the apparatus involved, whereas, if the operator had performed the regular routine of manual operation independent of all automatic devices the damage would probably have been prevented.

Every precaution should be taken in the installation of automatic-controlling devices to make their operation independent of the normal service conditions of the system, thus insuring their successful operation under any conditions which may arise.

In conclusion, too much stress cannot be laid on the careful testing of all pieces of apparatus to be installed on the system. All lines and apparatus should be periodically inspected and tested, and no expense should be spared in obtaining correct explanations of the causes of all trouble which arises on the system.

ROTARY CONVERTERS AND MOTOR-GENERATOR SETS.

BY WM. C. L. EGLIN, *Delegate Association of Edison Illuminating Companies.*

In the distributing systems of the electric-supply companies in the United States, the demand for low-tension direct-current service is usually of the first importance. The distribution is underground by means of three-wire network, fed from sub-stations located near the load centers; the sub-stations being connected by means of high-tension alternating-current feeders to the main generating station, which is located where the best facilities are available for economical operation. The sub-stations are usually provided with a storage battery, and in some cases with an auxiliary steam equipment, which is used in the event of emergency or for extraordinary loads during the winter months. In most cases, however, where auxiliary steam apparatus is used, it forms part of an old generating station which has been changed to a sub-station.

The percentage of the total load converted for direct current varies widely in different localities, and in the larger supply companies it varies from 30 per cent to 100 per cent. Some of the leading companies also supply power to the sub-stations of street railway companies, and others have a 500-volt power circuit, although most of the direct current is supplied on three-wire 230-volt systems.

In all cases the percentage of the total load converted from alternating current to direct current is large, so that an effective, reliable, and efficient means of transforming alternating current to direct current is essential. The three methods available for this purpose are rotary converters, motor-generator sets, and rectifiers, the first two only of which are available at present for transforming large currents.

ROTARY CONVERTERS.

A rotary converter is similar to a direct-current generator, with taps made on the armature winding and the addition of

collector rings to introduce alternating current. In a single phase rotary converter these taps would be made 180 deg. apart; for two-phase, 90 deg., and similar arrangements for polyphase systems. In most of the larger rotary converters using three-phase systems, the phases are split so as to use six phases on the rotary converter, and in that way increase the capacity of the machine. The efficiency of the rotary converter is higher than of the direct-current generator, for the reason that part of the current passes directly through the windings. The rotary converter must be operated in synchronism with the generator, and when started from the alternating-current side has all the characteristics of a synchronous motor. The rotary converter may be either shunt-wound or compound-wound. The voltage at the direct-current end of the shunt-wound type depends upon the voltage of the alternating current delivered to the collector rings, and practically cannot be varied without varying the alternating current impressed on it. Varying the field strength has the effect of changing the power factor, making the current either leading or lagging without materially changing the voltage delivered on the direct-current end. This necessitates some form of regulator on the alternating-current side so as to control the voltage on the direct-current end of the rotary. There are two methods, either the introduction of induction regulators in the alternating-current leads on each phase of the rotary, or dial switches on the step-down transformers, which vary the ratio between the primary and secondary winding. The step-down transformers are arranged so as to deliver the proper voltage for the e.m.f. desired on the direct-current side of the rotary; and, therefore, a rotary converter equipment consists of step-down transformers, regulators, and the rotary converter, with the necessary switches and safety devices.

Means must be provided for starting the rotary converter and bringing it to synchronous speed. The rotary may be started from either end, preferably from the direct-current side. When starting from the alternating-current side, the current required exceeds the full-load current usually from 50 to 100 per cent; and some means must be provided for controlling this large current; also the field must be cut out until synchronous speed is obtained.

When started from the direct-current side, the machine is started similar to the direct-current motor with variable resistances in the armature circuit, which is gradually cut out as the machine accelerates in speed. The rotary is then synchronized with the alternat-

ing-current generator similar to the operation of paralleling two alternators. Starting arrangements may be common for a number of rotaries, and this is arranged for by switches on the switchboard.

A third method which has been used on large rotary converters is the starting motor, using an alternating-current motor of the induction type to bring the machine up to synchronous speed. When only one rotary converter is in use, and direct current is not available for starting, and the rotary is, therefore, started from the alternating-current side, care must be exercised to test the polarity, as it is very probable it may be reversed. This can usually be rectified by opening the switch on the alternating-current side, allowing the machine to slip a pole.

The rotary converter meets all of the commercial conditions demanded of it, and is capable of delivering current on the direct-current side at from 110 to 600 volts. It can be operated on varying frequencies from 25 to 60 cycles successfully. Rotary converters operate better at the low frequencies for reasons which will be discussed later.

In the early introduction of rotary converters, difficulties were met which were principally due to hunting, usually caused by variations in the angular velocity of the generator. This caused a swing action of the revolving part of the rotary converter, which generally increased unless some means were provided to dampen this effect. The effect of hunting causes excessive sparking at the brushes, and when hunting becomes excessive the machine will flash over at the commutator and short-circuit the direct-current side of the machine; and unless safety devices are provided the machine is liable to be destroyed. The difficulty of hunting has been overcome by the addition of bridges between the poles of the machine. The design of these bridges was capable of being varied so as to increase the dampening effect required. The first form was a copper bridge placed between the poles, but it was found that additional dampening effect was required. The poles were then undercut and copper bridges were extended under the pole tips. The most powerful form consisted of a copper bridge imbedded in the pole face. The addition of bridges usually reduced the efficiency of the machine; rarely, however, exceeding 1 to 1½ per cent. The proper remedy for hunting is naturally the removing of the cause by obtaining a uniform rotation of the generator, which can be accomplished by the combination of an effective governor and the necessary fly-wheel effect on

the engine. Hunting does not seem to take place when the generators are driven by either steam or water turbines. A number of rotary converters have failed owing to the killing of the field, due either to the circuit being open or to the effect upon the field caused by disturbances on the alternating-current side, thus allowing the machine to exceed its normal speed, or, in other words, run away. These failures have required the installation of auxiliary apparatus and of safety devices, which are usually installed as follows:

A circuit-breaker on the direct-current side arranged to trip with excessive overload, which cuts out the rotary in the event of its flashing over at the commutator; and speed-limiting devices to trip the circuit-breakers on the alternating-current and direct-current sides. In some cases the alternating-current side of the rotary is provided with an overload and reverse-current circuit-breaker which trips when the current is reversed; or, in other words, when the rotary is running inverted, supplying alternating current to the line and taking direct current from the sub-station.

There are a number of different forms of speed-limiting devices, both electrical and mechanical. One form of electrical device consists of a differential relay, one set of coils being connected to the alternating-current bus and the other set to the collector rings. In the event of the rotary exceeding its speed, the frequency at the collector rings will increase, causing an unbalance at the relay and tripping the circuit-breakers. The mechanical devices usually consist of some governor attachments which make contact in the event of the shaft running above its normal speed and tripping the circuit-breakers. Various arrangements of the field wiring so as to allow combination separate and self-exciting connections have been tried so as to prevent errors on the part of the operators.

The study of the rotary converter from an operating standpoint early indicated that the machine had a high inherent efficiency; that the voltage and load could be easily regulated and the power factor adjusted to suit the best operative conditions of the system, and that the first cost of the outfit was comparatively low. For these reasons it was extensively used, especially for frequencies of 25 cycles.

Motor-Generator Sets.

Before the rotary converter had been fully developed, a number of these machines were installed on systems with frequencies of 60 cycles; and at this frequency the difficulties due to hunting were greatly increased, and in some cases satisfactory operation could not be obtained. This led to the introduction of the motor-generator sets. The first motor-generator sets were installed so as to obtain the most reliable equipment irrespective of the cost or efficiency. These equipments consisted of a low-voltage polyphase induction motor, direct connected to either one or two direct-current generators mounted upon a common base. The motors were arranged with stationary coils and squirrel cage winding on the rotor, and they were similar in most respects to the small motors which have been used successfully for a variety of purposes. The generators were of standard design and the motors were built to suit the speed of the generator; the motor being supplied with low-voltage current from step-down transformers. On account of using induction type motors the difficulties due to hunting were removed, and the operation in the sub-station was further simplified by having no electrical communication between the direct and alternating-current sides, thus removing the dangers of the machine running away.

The motor-generator sets can be started either from the direct or alternating-current side, by using the generator as a motor and placing a variable resistance in the armature circuit similar to the method used in starting the rotary converter. When the set is started from the alternating-current side, some current-limiting device is introduced in the alternating-current circuit leading to the motor. It has been found of advantage in practice to synchronize the larger motor-generator sets so as to prevent any sudden rush of current when throwing the motors on the system. As the usual methods of synchronizing are not suitable for this purpose, a disc with white and black stripes is attached to the shaft and with an arc lamp connected to the alternating-current bus, the set can be readily synchronized and at synchronous speed the black and white stripes are readily visible. By the attachment of mirrors to the pillow blocks of the various motors, each set can readily be synchronized by the switchboard attendant. Bringing the machine to synchronous speeds is not essential, although it is recommended for the larger size units; that is to say, machines of

400 kw or larger. It has been found advantageous to start both generators and rotary converters from the direct-current side with a starting bar operated by hand, thus reducing the amount of current required to overcome the friction of rest about one-half. This is often important when the sub-station is heavily loaded and the current is drawn from it to start additional machines. It also reduces the size of the starting resistance; for example, 400-kw motor-generator sets or rotary converters may require from 400 to 600 amperes to start them from rest, providing the machines have been standing for some time, and thus the oil allowed to squeeze out between the bearing and the shaft. With the assistance of the starting bar this current can be cut down to 200, and not exceeding 250 amperes at 230 volts.

The operation of these motor-generator sets was all that could be expected of them and was satisfactory in all respects; but, on account of their inefficiency and high first cost, improvements were demanded.

A very rational step was the abolishment of step-down transformers and the substitution of a high-tension for the low-tension winding on the motors; the introduction of one 250 to 300-volt generator instead of two 125 to 150-volt generators, and, in some cases, the substitution of a synchronous motor for an induction motor.

The use of the high-tension winding on the motor removed the necessity for and cost of the step-down transformers, and more than compensated for the additional floor space required by the motor-generator set. Regulators on the alternating-current side were unnecessary — the voltage on direct-current generators being readily controlled by a rheostat on the shunt field — and the operation was simplified, allowing the equipment to be handled by the regular class of dynamo operators, this being of great importance in large systems, as it requires less time to train the operators. Disturbances on the alternating-current side of the system have little effect on the motor-generator sets and are of such a character that they are easily provided for by protecting devices.

The objection to motor-generators, especially those of induction type, is the low-power factor, which increases the losses in the feeders. The losses in the feeders are usually a small part of the total loss, so that this in many cases is not important.

The first cost of motor-generator sets is usually somewhat higher than of rotary converters, particularly in the large sizes. The

actual difference, however, is not so great as is generally supposed. The relative costs of the various sizes are shown in the following table:

COMPARATIVE TABLE OF COSTS.

Rotaries with transformers and regs.		Synch. Mt. Gen.	Ind. Mt. Gen.	Synch. Mt. Gen.	Ind. Mt. Gen.	
25 Cyc.	60 Cyc.	25 Cyc.	25 Cyc.	60 Cyc.	60 Cyc.	Capacity.
1.00	1.05	1.05	1.10	1.03	1.08	1,000 kw
1.00	1.00	1.05	1.05	1.00	1.00	500 kw.
1.00	.95	1.00	.95	.95	.95	250 to 300 kw.

This is based on quotations by the same manufacturer of rotary converters and motor-generator sets of 25 and 60 cycles, with a 25-cycle rotary converter with transformers and regulators as a unit.

The following table shows the efficiency of a 400-kw, 60-cycle rotary converter and a 400-kw 60-cycle motor-generator set with both high and low-voltage motors. These tests were made at the works of the manufacturers, and show that even at high frequencies the rotary converter is more efficient than the motor-generator set:

Rotary Converter.

Two-phase, 16 poles, 400 kw, 450 r.p.m., 230 to 300 volts rotary.

Two-phase, 60 cycles, 5000 volts primary, 210 to 160 volts secondary transformer.

Per Cent. Load.	Combined Efficiency. at 210 Volts.	at 160 Volts.
100	89.6	90.5
75	88.0	88.9
50	84.3	85.5
25	73.0	75.3

Motor-Generator Sets.

Direct current, 10 poles, 400 kw, 450 r.p.m., 125 to 150 volts.

Alternating current, 16 poles, 560 kw, 450 r.p.m., 380 volts.

Per Cent. Load.	Combined Efficiency at 150 Volts.
100	82.0

Direct current, 10 poles, 400 kw, 450 r.p.m., 230 to 300 volts.

Alternating current, 16 poles, 560 kw, 450 r.p.m., 220 volts.

Per Cent. Load.	Combined Efficiency at 300 Volts.
100	84.9

Direct current, 10 poles, 400 kw, 450 r.p.m., 230 to 300 volts.
Alternating current, 16 poles, 560 kw, 450 r.p.m., 5500 volts.

Per Cent. Load.	Combined Efficiency at 300 Volts.
100	86.9

After these machines were installed in the sub-stations, a series of tests were made, using the same observers and the same instruments (the instruments being checked between tests), so as to obtain the all-day efficiencies when operating under commercial conditions; the rotary converters being placed in one sub-station and the motor generators in another, but both supplied from the same generating station. It would appear from these tests that there is no practical difference in the commercial efficiency between the high-voltage motor- generator set and the rotary converter, and, as was to be expected, the low-voltage motor-generator set was the most inefficient.

All-Day Efficiencies under Commercial Conditions.

	Type of Machine.	Load.	H. P.	Eff.	— Power Factor.— A Ph.	C Ph	Av.
No. 1	Ind. Motor	Empty	0	0.0	0.0	45.9	23.0
	Two-phase	1/4	140	72.9	67.1	86.4	76.7
	H. P., 560	1/2	280	82.1	83.6	92.8	88.2
	Volts, 220	3/4	420	85.3	86.4	90.4	88.4
	Amp., 1150	Full Ld.	560	85.4	88.7	92.1	90.4
No. 2	Ind. Motor	Empty	0	0.0	3.9	29.1	16.5
	Two-phase	1/4	140	72.7	56.9	69.7	63.3
	H. P., 560	1/2	280	81.2	77.4	82.5	80.0
	Volts, 6000	3/4	420	84.7	82.5	86.2	84.3
	Amp., 47	Full Ld.	560	85.9	85.6	88.9	87.3
No. 3	Rotary	1/4	134	70.9	99.2	106.0	102.6
	Two-phase	1/2	268	77.2	100.5	105.1	102.8
	KW, 400	3/4	402	80.4	97.4	102.4	99.9
	Volts, 250	Full Ld.	536	84.1	97.6	98.0	97.8

Conclusions.

The type of machine to be installed in sub-stations depends principally upon the frequency of the system and the importance

of reliable and continuous service. The frequency to be used depends upon other conditions which are outside the scope of this paper.

In cases where the largest percentage of the output of the generating station is to be transformed to low-tension direct current, 25-cycle rotary converters should be installed on account of their higher efficiency and lower first cost. The very large number of these machines which are now in successful operation proves conclusively their reliability and effectiveness. In mixed systems, and where the percentage of current transformed for low-tension distribution is small, motor-generators are desirable. With higher frequency, particularly 60 cycles, it has been shown that motor generators compare favorably in efficiency and are much more reliable and simple in their operation.

Discussion.

Chairman Ferguson: Mr. Eglin's paper is now ready for discussion. You know that in Europe motor generator sets are used very much more extensively than in this country, and we shall be glad to hear from any of our European friends as to their experience. Col. Crompton, we will be glad to hear from you.

Col. R. E. B. Crompton: I am unable fully to discuss this important subject as I have not studied the paper sufficiently carefully but I can communicate one figure which appears important — that is, that in the large London system with which I have most experience, where we generate and transmit at 5000 volts transformed by motor generator sets to 400 volts, and charge batteries through these sets; the total losses, including those in the high-pressure mains, motor transformers, accumulators, low pressure mains to consumers, amount to 27 per cent as a maximum, but about 25 per cent on the average. If we used rotary transformers, these losses would be greatly reduced.

Mr. Philip Torchio: In comparison with the efficiency obtained from motor-generator sets, I would say that with 25-cycle rotary converters of 500 to 1000-kw capacity, in American cities the all-day efficiency is above 90 per cent.

Mr. M. J. E. Tilney: The writer mentions that he only starts up from the direct-current side, owing to the heavy starting current. There is a large system in London where they start up from the high-tension side, with resistance in the rotors, and they find the maximum current never exceeds the full-load current of the machine, and in many cases is only 60 per cent. Is there any special advantage in starting from the direct-current side?

Mr. Philip Torchio: I want to add another point, and emphasize a matter that Mr. Eglin touched upon in the paper, but in my opinion, did not dwell upon strongly enough; that is, the advantage of the greater

capacity you get from a rotary converter than from a motor generator set for overload conditions. This is an important factor in laying out the reserve capacity for a sub-station.

Mr. EGLIN: The figure given by Col. Crompton is similar to the figure in this country on motor-generator sets. As to the question of cutting down the starting current, it is not the practice in this country to start from the alternating side. As the motor-generator sets are started from the direct-current side, the starting current would be much smaller than 60 per cent of the full-load current of the motor. It would not exceed 25 per cent. The motor-generator sets are started in the same way as the rotary converters are started, using the generator as a motor.

THE BOOSTER MACHINE IN TRACTION SERVICE, AND ITS PROPER REGULATION.

BY PROF. DR. GUSTAV RASCH.

In power stations for electric railways, especially for those feeding a network having a small number of cars running at the same time, there is a demand for a device to steady the power-station service. The unsteady load and current consumption in such power-stations grows worse as fewer cars are running at the same time on the line. It is known that ammeters and voltmeters of small power-stations indicate fluctuations continually, while large power-stations show mostly a steady load with small variations only. The disadvantages of the unsteady service with regard to the efficiency and the life of the steam-engines and the generators of the power-stations are obvious. It is desirable also that the cars, especially those cars running on the outer ends of the line, be fed with a constant voltage, which, however, cannot be expected from a power-station having too heavily fluctuating a load. To steady the machine service, a buffer storage battery is often used; that is, a floating battery connected parallel with the power-station generators. It is indisputable that such batteries possess valuable features. For instance, they are of great importance in case of breakdown of the machine service and they give a chance to run some cars just before starting up and after shutting down the regular power-station service. They have a disadvantage, however, in that they do not react upon the fluctuations of the current, but only upon the voltage. Though an absolutely steady voltage on the bus cannot be assumed, it is evident that the battery does less work as a buffer battery the steadier the voltage. It is very likely, however, that even with nearly steady voltage the machine may be subject to heavy fluctuations.

The following discussion may explain these phenomena still more clearly. The generator at the railway power station is shunt-wound, and, to simplify the discussion, it may be assumed that

the e.m.f.$=E$, may drop proportionally with rising current I_1 that is may follow the law $E=E_0-I_1c$ where E_0 is the electromotive force with no load, and c a constant. The constant c, may cover the influence of the armature reaction and the drop of speed of the machine with increasing current I_1. It has evidently the character of a resistance. The armature resistance of the machine is r (Fig. 1). The parallel connected buffer battery may

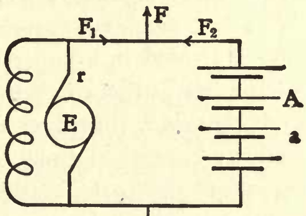


FIG. 1.

have an electromotive force A and an internal resistance a. The heavy fluctuating current in the network (the actual line current) is I, while I_1 and I_2 are the currents of the machine and the storage battery.

It is easy to derive the formula,

$$I_1=\frac{E_0-A+aI}{a+c+r} \tag{1}$$

$$I_2=\frac{(c+r)\ I-(E_0-A)}{a+c+r}. \tag{2}$$

At the average value I_m of the actual line current, the current of the storage battery must reach zero value, so that the battery may not be either overloaded or underloaded during daily service. That is, following equation (2):

$$o=(c+r)\ I_m-(E_0-A), \text{ or,}$$
$$E_0-A=(c+r)\ I_m.$$

That changes the equations (1) and (2) to

$$I_1=\frac{(c+r)\ I_m+aI}{a+c+r} \tag{3}$$

and,

$$I_2=\frac{(c+r)\ (I-I_m)}{a+c+r}. \tag{4}$$

It is necessary to make ample estimate of I_m.

The equation (3) shows that an absolute steadying of the machine

current I_1 is impossible, because it is not independent of the heavy fluctuating actual current I. The larger the value of $c + r$, and smaller the value of a, the larger will be the dampening effect. The first means high internal resistance and large drop of voltage, features of the generators which cannot be called desirable ones. A small storage battery resistance a, means plates of large surface, that is expensive cells.

The buffer machine (booster) is another means of steadying the service. The value of such a machine, especially for hoisting installations, was thoroughly treated in a paper by Mr. Meyersberg,[1] read at the meeting of the Institution of German Electrical Engineers. It is indisputable, however, that these machines are also of great value for all railway central stations, and for all similar services with load fluctuations of short duration.

A large centrifugal mass is driven by an electric motor (under certain conditions two motors may suitably be used). The armature of the motor is in multiple with the network. The centrifugal mass naturally accumulates energy with decreasing network current and gives out energy in the network with increasing current consumption. Therefore the buffer machine works at one time as a motor, and at another time as a generator. For the moment we will not consider the character of the field excitation of this machine. It will be the object of this paper, however, to calculate the most favorable device for one special case.

It may be assumed that the actual current I, of a 600-volt power station for a small railway is the subject of regular fluctutations from 500 to 200 amperes inside of periods of 12 seconds. The condition regarding the regularity of the sequence of the fluctuations is of minor importance; it is important, however, that the utmost data be obtained regarding the fluctuation itself; that is, 500 and 200 amperes be not increased or decreased, because otherwise the buffer machine would be forced to run at a speed which would not agree with the speed which was assumed when designing the machine.

The curve *A B C D E* (Fig. 2), shows the actual current fluctuation inside of one period. The average current of the generator ought not to be

$$\frac{200 + 500}{2} = 350 \text{ amperes,}$$

1. Meyersberg, *Elektrotechnische Zeitschrift*, 1903, page 261.

but somewhat higher, about 360 amperes, on account of the efficiency of the buffer machine, which is naturally below 100 per cent. With absolutely equalized service the generator would work continuously with this amount of current. One may be satisfied, however, in practice to limit the fluctuations to 10 per cent above and below this amount. We therefore assume that the generator current I_g must be dampened by means of the buffer machine to the limits of fluctuations between 400 and 320 amperes (see curve A_1 B_1 C_1 D_1 E_1 in Fig. 2). Now then, $I_g + I_p = I$, and it follows that the buffer current $I_p = I - I_g$. The curve A_2 B_2 C_2 D_2 E_2 Fig. 2, shows the work of the buffer current I_g. The positive values mean taking energy (charging), the negative values, giving out energy (discharging) by the buffer machine. For the moment, the e.m.f. may be assumed as constant, at 600 volts, the output of the

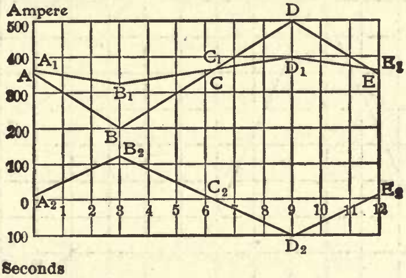


Fig. 2.— Output of generator and buffer.

buffer machine being a maximum during charging:

$$600 \; (320 - 200) = 72{,}000 \text{ watts.}$$

This value may be used as specific for the designing of the buffer machine, though naturally there is the intermittent service to be taken care of in addition.

The curve A B C D E (Fig. 3), shows the period of loading and unloading the buffer machine. This figure shows a time phase retardation against Fig. 2, inasmuch as the period starts with the beginning of the load. It shows that the loading has a duration of 6.54 seconds, and the unloading a period of duration of 5.46 seconds. The energy consumption is,

$$\frac{72{,}000}{2} \times 6.54 = 236{,}000 \text{ watt-seconds.}$$

The energy output is:

$$\frac{60{,}000}{2} \times 5.46 = 164{,}000 \text{ watt-seconds.}$$

The total efficiency is therefore assumed as

$$\frac{164,000}{236,000} = 0.695$$

corresponding to an efficiency of

$$\sqrt{.695} = .834$$

for the single conversion of electric energy to mechanical energy, or *vice-versa.* If a lower average current of the generator were to be assumed, the efficiency would be proportionately higher. It may be practical to reckon with more than 83.5 per cent efficiency; which was purposely not done, however, for the reason to be mentioned in the latter part of this paper.

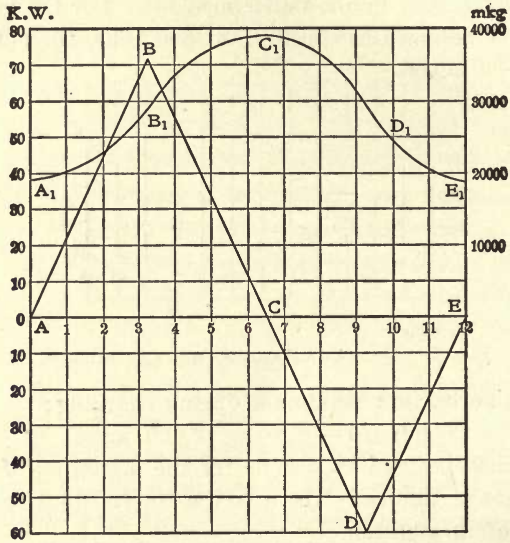


FIG. 3.—ENERGY AND POWER OF BUFFER.

We will not define how much of the energy stored in the centrifugal masses is to be used, but state only that at the end of an unloading period there has still to be stored an energy L_e + mkg This energy storage will be

$$L = L_e + .834 \ \frac{236,000}{9.81}$$

That is,

(5) $$L = L_e + 20,000 \text{ mkg.}$$

If U is the highest speed per minute, we have

(6) $L = c\ U^2$, c being a constant, the value of which is of no

interest at this place in the discussion. If $(1-s)\ U$ is the smallest allowable speed of the fly-wheel (s being the slip), we will have

$$L_e = c\ (1-s)^2\ U^2 \tag{7}$$

from (6) and (7) may be derived:

$$\frac{L_e}{L} = (1-s)^2 \tag{8}$$

and in connection with (5), we may write:

$$L = \frac{20{,}000}{2s - s^2} \tag{9}$$

The amount of slip s is, therefore, of fundamental influence. Large values of s (for instance $s = .5$) allow the use of relatively small fly-wheels, the specification for which is determined by the value of L. On the other hand, however, the reserve of energy is very small with large slip. On the end of a normal unloading period, the vis-viva of the fly-wheel has diminished to:

$\frac{L_e}{L}\ 100 = 100\ (1-s)^2$ per cent of the starting value. This represents the reserve for exceptionally large unloading, decreasing with increasing slip, as shown by the following table:

	$s = .2$	.3	.4	.5
$100(1-s)^2 =$	64%	49%	36%	25%

Another reason against increasing the slip is, that the dimensions of the buffer machine increase with low speed. With large slip, however, the average speed will be lower than with small slip.

Remembering, therefore, that large slip calls for small centrifugal masses only, but for large buffer machines, and *vice-versa,* and that small slip calls for large centrifugal masses and small buffer machines, it is evident that the proper amount of slip to be chosen is one of the problems which come up often in engineering,— that is to find out the conditions under which the sum of the first cost of two parts of a machine is a minimum. This problem, however, is not to be solved generally, but can be solved only in each case, by approximation, giving due weight to all practical questions. We will not dwell upon this problem, but assume that we did find as most favorable value, $s = .3$. That would give us, following the equation (9), the maximum vis-viva

$$L = 39{,}200 \text{ mkg.}$$

Incidentally at this place may be answered the question why

special buffer machines are used instead of using heavier centrifugal masses in connection with the generator itself. This question answers itself, if one observes the fact that in the latter case the slip would not be more than 5 per cent; for $s = .05$, however, it follows from equation (9) that

$$L = 205{,}000 \text{ mkg.}$$

Assuming the same peripheral speed of the fly-wheels, the weights of the fly-wheels are proportional to the vis-viva, and, to get the same effect, the fly-wheel connected to the generator would have to be made five times as heavy as that driven by the buffer machine.

Returning to Fig. 3 and choosing a scale for the vis-viva, we may draw on this scale the ordinate:

$$A\,A_1 = L_e = 39{,}200\ (1 - .3)^2 = 19{,}200 \text{ mkg.}$$

The loading time (AC Fig. 3) amounting to 6.54 seconds is to be divided in two parts of 3.27 seconds each. In the first part the energy put into the fly-wheel per unit of time is increasing, while in the second part it is decreasing. The effect transmitted to the buffer machine in the first part of the period at the time t is:

$$72{,}000 \frac{t}{3.27} \text{ watts.}$$

The amount of energy accumulated in the fly-wheel at this time t is:

$$L_t = 19{,}200 + \frac{.834}{9.81}\ \frac{72{,}000}{3.27} \int_0^t t\, dt = 19{,}200 + 935\ t^2 \text{ mkg.}$$

This gives us the means of calculating the several ordinates of the curve $A_1\ B_1$. Following the same formula, the vis-viva at the end of the first part of the loading time is found to be 29,200 mkg. For the second part, a similar simple calculation results in,

$$L_t = 29{,}200 + 935\ (t - 3.27)\ (9.81 - t)$$

where t is increasing from 3.27 to 6.54 seconds. The developing of the formula for the vis-viva with unloading fly-wheel may be derived in a similar way. It should be considered, however, that the efficiency of the buffer machine is to be regarded as the divisor of the expression. For the third interval:

$$6.54 \leqq t \leqq 9.27, \text{ we have}$$

$$L_t = 39{,}200 - \frac{1}{0.834 \times 9.81}\ \frac{60{,}000}{2.73} \int_{6.54}^{t-6.54} (t - 6.54)\, dt$$

$$= 39{,}200 - 1340\ (t - 6.54)^2.$$

This course is shown in curve $C_1 D_1$. In the fourth interval there is,

$$9.27 \leqq t \leqq 12 \text{ and } L_t = 19{,}200 + 1340\ (12 - t)^2.$$

interval.

The curve $A_1\ B_1\ C_1\ D_1\ E_1$ Fig. 3, shows the course which the vis-viva has to follow if the buffer machine is to regulate in the way shown in Fig. 2.

The next question is: How is the speed to be changed in order to get this course of the vis-viva. We have to follow the earlier mentioned equation (6),

$$L = c\ U^2.$$

It refers to the maximum value of the vis-viva and speed, but may be used just as well for every other value. Thus substituting L_t and U_t, we obtain:

$$(10) \qquad L_t = c\ U_t^2.$$

From the equations (6) and (10),

$$\frac{L_t}{L} = \left(\frac{U_t}{U}\right)^2 \quad \text{or}$$

$$(11) \qquad u\ .\ \sqrt{\frac{L_t}{L}}\ .$$

One is not limited in the choice of maximum speed. The weight G (kg), the peripheral speed $v \left(\frac{\text{m}}{\text{second}}\right)$ and the vis-viva L, are (a plain cylindrical fly-wheel being assumed) in the relation,

$$L = \frac{v^2\ G}{4 \times 9.81}.$$

With a peripheral speed of 45 m. per sec., there is, therefore,

$$L = 39{,}200 \text{ and } G = 760 \text{ kg.}$$

In order to avoid too large fly-wheel weight, it is suitable to use a high peripheral speed. Speeds of 60 m. per second, and over, have been proposed for fly-wheels of suitable construction. There still remains the choice of speed. It is not necessary to determine now the exact number of revolutions. It is sufficient to assume as maximum value

$$U = 100$$

and to express the different values of speed in per cents of this maximum value. From the values found for the vis-viva the necessary number of revolutions are derived, shown in the curve $A\ B\ C\ D\ E$ in Fig. 4. The load of the buffer machine is transferred

to this figure from Fig. 3. It is to be seen that the buffer machine has its highest load at a moderate number of revolutions, — (in our case 86.3 per cent).

It was assumed that the voltage on the busses was constant. Naturally this does not apply in practice; it will decrease with increasing current consumption, and *vice-versa.* Therefore, it will be higher when loading the buffer machine than with unloading. That is, the storing of energy while loading the buffer machine will be favored; the unloading on the other hand will interfere with

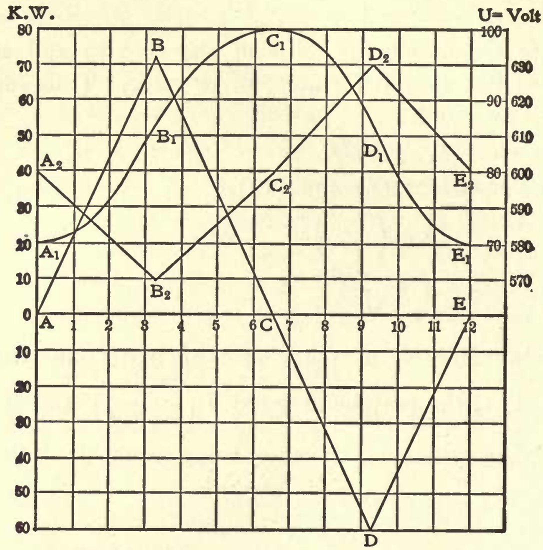


FIG. 4.—ENERGY AND POWER OF BUFFER.

the giving up of energy. Unsteady voltage will have the same influence as a resistance in the armature circuit of the buffer machine, resulting in a lower efficiency, which was chosen rather low for this reason. The question is now to decide upon the factors which could be used to improve the regulation:

These are,

(1) The voltage,

(2) Buffer current I_p,

(3) The actual line current I,

(4) The generator current I_g,

(5) The speed.

The same objections hold true for the voltage, which have been developed in the discussion of the buffer battery. If the buffer

machine is simple shunt wound, it will be influenced by the voltage. This would not allow the regulation of such heavy fluctuations as defined in our above calculations, and the energy consumption and the restoration of energy by the fly-wheel would take place within much narrower limits.

Fig. 5 shows that the current of the buffer machine cannot be used for regulating purposes. Fig. 5 is derived from Fig. 4, using load and unloading current as abscissa, and the desired revolutions per minute as ordinates. The curve shows that to any value of the current there belong generally two different values of the speed,

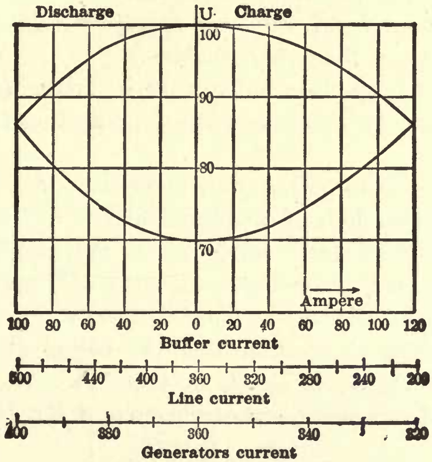


FIG. 5.

the difference of which is the greater as the current is lower. Obviously, this condition is not to be reached in practice. However, we may influence the regulation by the current, one value of it will always call for only one definite value of the speed. The same considerations regarding the buffer current holds true also for the actual line current and for the generator current. To Fig. 5 are added values of the actual and generator current, which prove in this case that a suitable regulation cannot be reached, since *one* of them, decreasing or increasing according to the network current load, cannot produce two different speeds of the buffer machine. It would be possible to influence the field of the buffer machine by the combined buffer current and line current, in addition to a special shunt winding fed from the bus, but even this would not give the correct result. We wish to transmit the fluctua-

tions of the line current to the buffer current, which means that both of them must reach their highest values simultaneously, as shown in Fig. 2. The two currents working in two different windings on the magnet field of the buffer machine would, according to the way they were connected, work either with or against each other. In the first case they would not reach the desired result; in the second case, the result would be equal to that which could be reached with one of the currents alone, which is not suitable, as above mentioned.

The question of making use of a change in speed for regulating the buffer effect gives us two possibilities:

(1) Using a centrifugal regulator to adjust a rheostat placed in the field winding of the buffer machine.

(2) The use of a special exciter machine driven from the buffer machine, and having therefore a speed proportional to that of the buffer machine.[2]

The latter seems to be the most favorable, since this regulation is not applied step by step, but gradually.

We assume again a steady voltage on the bus, and assume furthermore that the e.m.f. of the buffer machine with maximum current varies from 5 per cent above to 5 per cent below this voltage; in this case the vibration of e.m.f. during the period of 12 seconds is shown in the curve $A_2\ B_2\ C_2\ D_2\ E_2$ (Fig. 4). The proportion of the ordinates of this curve, and of the curve $A\ B\ C\ D\ E$ — that is

$$\frac{E}{U} = \frac{\text{E M.F.}}{\text{speed}}$$

are proportional to the lines of force which are necessary for the field of the buffer machine to produce the desired regulation. Fig. 6 shows a diagram, the abscissae of which are proportional to the value $\frac{E}{U}$, and the ordinates proportional to the speed. In this case there are also generally two ordinates for one abscissa, but the difference in the most unfavorable case is 8 per cent, while the regulation by means of the currents showed differences of 30 per cent (Fig. 5). If both branches of Fig. 6 could be combined — which would call for no armature resistance whatever in the buffer machine — the regulation would be a perfect one. We remark, therefore, that a low armature resistance is favorable.

2. Both kinds of regulation are the subject of the German patents No. 129,553, assigned to the German General Electric Co., Berlin.

The connections may be as follows (Fig. 7):

The buffer machine P is provided with two field windings M_1 and M_2. M_1 is excited from the busses; M_2 from a small generator e,

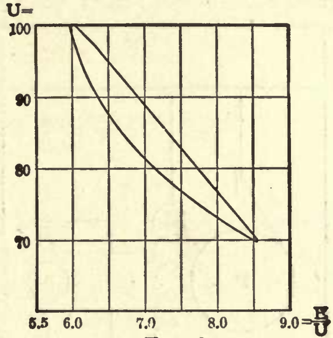


FIG. 6.

placed upon the axle of the buffer machine, and excited from the bus also. The windings M_1 and M_2 are differentially connected, so that with increasing current in M_2, the total field of the buffer machine will be weakened.

Another arrangement would be to use a part of the winding M

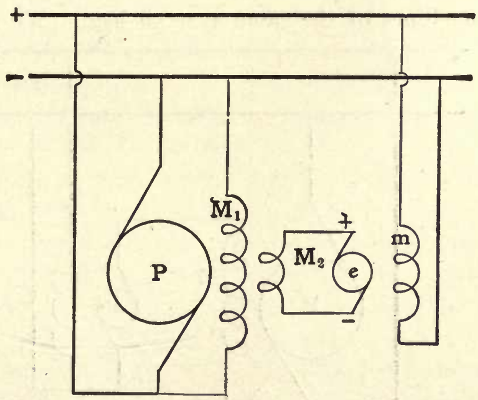


FIG. 7.

as the second winding M_2, as shown in Fig. 8. The latter arrangement has the advantage of a smaller winding space necessary for the buffer machine; it has the disadvantage, however, that the small machine e has eventually to be designed for rather high voltages, while with an arrangement according to Fig. 7, voltage and current of the small generator may be chosen at will.

The small generator may also be designed as motor, the armature of which is to be connected in series with the magnet winding *M* of the buffer machine (Fig. 9). In this case increasing the speed of the buffer machine will cause an increase of the e.m.f. of the

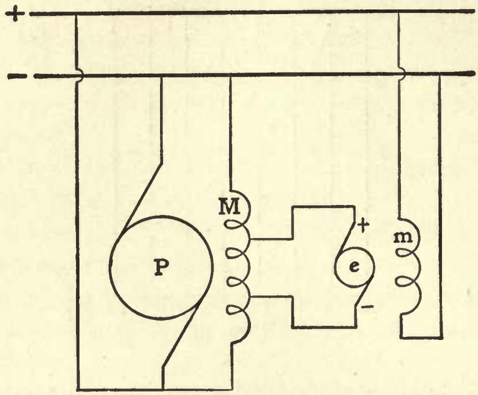


FIG. 8.

small machine, and result in decreasing the exciter current of the buffer machine. In all arrangements, while working, there is a weakening of the field of the buffer machine, and, therefore, the dimensions of these machines must be made ample, in comparison with other machines of the same average load. We may mention

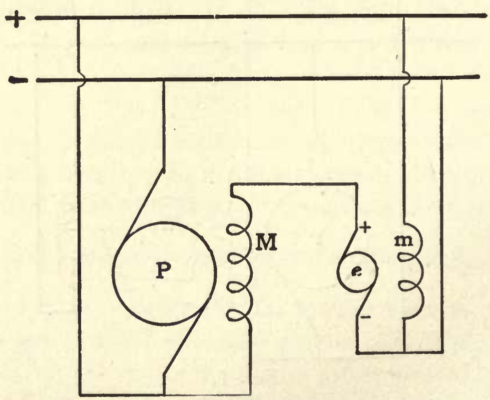


FIG. 9.

that in all cases the maximum armature current of the buffer machine does not reach its highest value at the same time with the weakest field, but with an average strong field, which, of course, is favorable.

The discussion has shown that the most suitable regulation of the buffer machine is to be effected by means of speed regulation.

STORAGE BATTERIES IN ELECTRIC RAILWAY SERVICE.

BY JUSTUS B. ENTZ.

The principal applications of batteries to electric railway systems are made at the generating stations, at distributing sub-stations, and directly connected to points on a direct-current distributing line. The objects of such installations are to store electrical energy at efficient and convenient periods and to return it when most useful, generally at periods of increasing or heavy load. A storage battery, which is a reservoir of electrical energy, when connected to the circuit, makes the conditions of generation and transmission up to the point where the battery is connected independent of the load demand of the circuit beyond that point. The storage battery also permits the rate of production of energy to be independent of the rate of demand. The demand for electric current may occur at a time when its production will be inconvenient or inefficient, or both, The demand may call for a very high rate of output for a short time, as in electric railway systems, where the maximum demand lasts only for a period of a few seconds. By the use of a battery the rate of producing energy may be adjusted with reference to other considerations, such as efficiency of generating apparatus. This energy may be produced at low and constant rates and stored in a battery and given out to meet the demands of variable and very high rates. The results thus obtained are improved efficiency of operation and greater reliability of service.

In comparing a battery with the generating and transmission apparatus, it will be noted that the battery handles most economically those portions of the load which are least economical for generating or transmission apparatus, namely, those which are of extremely short duration and excessive in amount, as well as those which are of considerable duration, but of very small amount. The maximum economy of usefulness is secured by such division of load between the battery and other apparatus that each handles that portion to which it is best adapted.

The reasons for installing storage batteries in railway work are as follows:

1). Reasons affecting investment.

2). Reasons affecting economy of operation.

3). Reasons affecting reliability and public convenience and safety.

It is impossible to draw a sharp line between the three classes of reasons. A part of the total investment for railway equipment is made for economy or for reliability. The consideration of a battery in this class of work usually involves the comparison of battery with generating machinery, or in some cases the transmission copper and sub-station equipment, or with all of them on the three headings enumerated above. In such a comparison the following points must be considered:

1). The results of the comparison of investment will depend upon the shape of the load diagram and upon the methods and distances of transmission and upon what portion of the load is assigned to the battery. In general, however, it may be stated that there is almost invariably some portion of the maximum load which may be carried by a battery at an investment cost not exceeding that for the apparatus it actually displaces to do the same work. It is often sound engineering to increase the proportion of the battery considerably beyond that point to secure more fully the advantages in headings 2 and 3; and it must be borne in mind that many of the functions of a battery can be performed by no other class of apparatus, and where these functions are vital, the investment comparison is of minor importance.

2). Under the head of economy of operation must be included both generation and transmission of energy and both labor and fuel economy, as well as cost of maintenance and depreciation. As loads of certain nature are handled more economically by the battery than by generating machinery, the maximum fuel economy is secured by such division of load between the battery and machinery that each handles that portion for which it is best adapted.

The question of the size of a power equipment is, of course, confined to a determination of the requirements necessary to meet the maximum load conditions, whereas, considering economy of operation, the average load conditions must be considered. In the sub-station there is an increased efficiency of rotaries and transformers due to the operation of batteries which must be compared with the losses in the battery. With the batteries used very con-

siderably on peak work, their output will amount to from 15 to 20 per cent of the total output of the station. As the battery under average conditions will not be fully used, but a certain portion of it held in reserve to meet abnormal conditions, the efficiency of the battery will be high. Taking this at 85 per cent as a minimum, we find that the losses in the batteries, where their output is 20 per cent of the total, is 3 per cent of the total output of the system.

It is safe to say that on account of the improved efficiency in transmission and the improved load factors on the rotaries, the efficiency of the sub-station should be increased by considerably more than this amount, and that any improved economy in the generation of power at the main power-house will be net gain.

The economies at the power-house from the operation of batteries will be such as to produce ideal economy in both boiler and engine-room. The load on the engines and boilers can be adjusted to practically the 24-hour average, and need be varied only when this average is changed. With peaks in the morning and evening to double the height of the average load, this will mean operating through the day at practically one-half the capacity that will be needed at the peaks without the battery. To handle these peaks without the battery, it would be necessary to keep one-half of the total boiler capacity with fires banked from 18 to 20 hours a day for operation during the hours of peaks. The constant loss in these boilers through radiation and the escape of heated gases would probably not be less than 20 per cent of their capacity; and one-half of these losses, or 10 per cent of the boiler capacity required with the battery in service, would be saved. This would mean a saving of 10 per cent of the total fuel.

The improved load factor on the engines and generators and the reduction in the number of engine hours of operation would effect an additional economy. There is a considerable loss of steam when every unit is started up, this being the steam consumed from the time the throttle is opened to the time the load is thrown on the generator. As the operation of batteries would reduce the number of times the unit is started up and shut down, there would be a saving on this point. I believe that it would be conservative to expect a saving on this point of from 5 per cent to 10 per cent, making a total saving of fuel in the operation of a power plant with batteries of from 15 to 20 per cent.

It has been stated that a storage battery is a good thing to patch

up bad engineering. This is true, and there is a considerable field for its application in this way. It is, however, not limited to such cases, and is often the only means of preventing engineering proving to be bad owing to the impossibility of foretelling what conditions are to be met exactly. The extreme flexibility of a battery in meeting conditions varying over a very wide range renders it peculiarly applicable to such cases.

Under the question of maintenance and depreciation it may be noted that with a storage battery these two items are combined in one. The renewals of plates which are made from time to time keep the battery up to date, so that at the end of a period of years it is not an obsolete piece of apparatus, but it is up to date in every respect and equal to the batteries then in the market, including all the improvements in plate construction which have been introduced since it was installed. The flexibility of the battery to meet changes in conditions, such as desirability of increased voltage or larger capacity, is also to be noted, such changes in conditions often involving the discarding of generating apparatus; whereas in a battery, the simple modification in the number of cells, or the number of plates in each cell, will suffice.

3). The reliability of the storage battery and its absolute freedom from break-down without warning is due in part to the fact that it is composed of a multitude of small units, each unit being a battery plate, any one of which can be put out of service without noticeably affecting the operation of the entire installation; whereas, in a generating plant, the various parts, such as boilers, engines, generators, switchboard apparatus, transmission lines, transformers, and converters, are all connected in series and the derangement of any one class of these parts instantly interrupts completely the operation of the whole. The deterioration of a battery is in all cases very gradual, and repairs can be made without taking the battery out of service.

As an emergency reserve, the battery can be found of immense value in any one of the following ways:

a). In case of a total shut-down of the power-house or high-tension lines, the amount of battery which would usually be installed from other considerations would be sufficient to maintain the entire service of the road at the time of the peak for three-quarters to one and one-half hours, or for twice as long during the middle of the day, thus permitting temporary repairs to be made. In case of an interruption of longer duration, the battery would at least en-

able the trains to be run into the station and the passengers discharged, instead of leaving them stalled between stations.

b). At a sub-station the rotaries could be shut down for an indefinite period of time, the battery being floated on the line at a somewhat reduced voltage.

c). The batteries are available instantly to take care of sudden excessive load of short duration, due to any unusual congestion of traffic.

d). They will take care of and prevent interruptions from short-circuits on the line which would otherwise fall on the machines, saving overloading them and then throwing out the breakers and interrupting the traffic.

e). The batteries would permit the entire machinery of the power-house and sub-station to be shut down at night and the current cut off the alternating-current lines for a period of several hours for repairs and inspection.

f). The batteries would often make it possible to purchase either alternating or direct current from other systems at times when they were not overloaded, and at a constant and controllable rate which would cause no disturbance. This power could be utilized on the system at times of peak load, when it probably could not be purchased.

The fact that the batteries are available in case of emergency would permit the shutting down of machinery when signs of trouble first appear, thus reducing the extent of the damage which might be caused by continuing to run partially disabled machinery until a substitute could be put in service.

The points enumerated above apply to batteries installed at the power-house and those installed on the line. Certain additional advantages arise in many cases from installing a battery at some distance from the source of power, due to the improved conditions of transmission. With such a battery, it becomes necessary to transmit only the average power required instead of the maximum. The result will be a saving in the amount of copper required for a given drop in voltage, or an improvement in the voltage with a given amount of copper, or the advantages may be divided between the two methods. An increase in economy will also be secured, since it is a well-known fact that to transmit a given amount of energy over a certain conductor in a given time, with a minimum loss, the rate of transmission should be constant.

The installation of a storage battery at a generating station is

to take the peak of the load for its maximum two or three hours, and to regulate or control the rapid fluctuations of load occurring all day. Where the station voltage has not a drooping characteristic it is necessary to add to the voltage of the battery the voltage of an auxiliary generator, in order to cause it to discharge at the time and by the amount necessary. This auxiliary generator, commonly called a booster, also serves for charging the battery without varying the bus-pressure of the station by adding its voltage to that of the bus, the armature of the booster being in series with the battery and its field strength being automatically controlled where the changes of load are at all rapid. When located at some distance from the power-house, the booster may be dispensed with, as the variation in the line voltage will be sufficient to cause the battery to do its work. Located in this way the battery will maintain the voltage on the line at approximately its average point. If the number of cells in the battery are properly adjusted to float this average voltage, the battery will remain in the same average state of charge. If the average voltage at the point where a line battery is located is found too low for satisfactory results, a booster may be installed at the power-house and sufficient current transmitted over a feeder direct to the battery at a voltage higher than the bus to maintain the battery voltage at the desired point, this latter arrangement affording means for adjusting the voltage at the battery to meet changes in local conditions — which is usually very desirable.

Such installations are very satisfactory and economical, showing a saving in investment over copper and generating machinery, as well as a considerable saving in energy, as not only is the energy transmitted at its average current value to such a point on the line, but the average current consumption is lessened by the increase of voltage at the point of consumption; and this increase and maintenance of voltage very often brings about an actual reduction in wattage at the point of consumption, because of the higher acceleration rates permitted by the cars themselves, resulting, as is well known, in a considerable reduction in energy consumed where stopping and starting is at all frequent. A booster for such a purpose is usually an independently excited booster located at the power-house and hand-controlled, so as to have control over the average output over the battery feeder.

The automatic control of a battery by its booster when the battery is connected in parallel with generating machinery of a constant or rising characteristic is accomplished in one of the following ways:

A regulating battery is generally discharged at a rate at least as high as its one-hour rate; that is to say, the rate at which it would discharge continuously without its voltage drop becoming too great. This does not mean that a battery is totally discharged at this rate in one hour's time, as a reduction in the rate would permit considerably greater capacity to still be taken out of the battery without its voltage falling too low. Within the full range of the one-hour capacity of a battery the voltage change for a change of the one-hour rate of current is from 5 to 7 per cent, due to the internal ohmic resistance of the battery, and this change of voltage is simultaneous with the change of current. If the full rate of current be maintained for 30 seconds, an increased change of voltage of from 4 to 5 per cent will take place in about 30 seconds' time, due to polarization. After 30 seconds the increased change of voltage due to polarization is comparatively slight, except at the very end of discharge or of a full charge. The booster must, therefore, be provided so as to give a voltage of about 12 per cent of the battery voltage at the time that the battery is charging or discharging at its maximum rate; and we must further insure that it will give a voltage of 20 per cent of that of the battery at a rate of current of from one-third to one-fifth that of the maximum rate, in order to bring the battery up to a point of full charge. The characteristic of most boosters allows them to give this additional voltage at reduced current with but comparatively little increase in the size of their field magnets.

The automatic excitation of the booster field is accomplished either by including an exciting coil in the working circuit by means of which the full output of the station to be regulated passes through this coil, so that an increased load demand strengthens the booster field and gives added voltage to the battery circuit sufficient to cause it to discharge by an amount equal to the increase, thus keeping the load on the generator constant, or to take any proportion of the increased load that is desirable. Such a main exciting coil in the working circuit must be neutralized by a separate exciting coil, so that with any predetermined average output of the station the booster shall neither add nor oppose its voltage to that of the battery. For currents below this established load, this opposing coil becomes stronger and reverses the polarity of the booster, causing the battery to charge by the proper amount to maintain the regulation desired. In order to make such a combination as stable as possible, another main-current coil has been included in the gener-

ator circuit, so that an increase of current falling upon the generator following an increase of outside load would further affect the battery and cause it to discharge. Where the outside main-current coil has been adjusted to exactly meet the state of the battery and so effect absolutely constant current delivered from the generator, this inside coil in the generator circuit, of course, accomplishes no purpose; but it prevents any lack of exact adjustment affecting the regulation to any great degree, and where very perfect regulation is required, this form of booster is very extensively used and is generally known as a differential booster.

Regulating altogether by variations in the generator load while trying to keep that variation within small limits, calls for some means of magnifying the effect of such variations upon the booster excitation. There are two methods of this kind in general use, in one of which a small generator with a voltage normally equal to that of the station bus has included in its circuit the exciting coil of the battery booster. When the voltage of the small generator and that of the bus are equal, no current flows through this booster exciting coil. This small generator is known as a counter e.m.f. generator, and derives its field excitation, and, consequently, its voltage, from a coil placed in the generator circuit, the said coil being so adjusted that the average load that is to be kept upon the generator produces a voltage of the counter e.m.f. generator equal to and opposed to that of the station voltage, so that under such conditions the battery is neither charging nor discharging. If, now, the generator output increased 10 per cent, the voltage of the counter e.m.f. generator, if it has a perfectly straight characteristic, will increase 10 per cent above the station voltage, and this excess of voltage should be sufficient to excite the booster to an extent necessary to cause the battery to discharge the balance of the load increase which caused the increase upon the generator, part having fallen upon the generator for the purpose of effecting the regulation. The lowering of the generator output following the lowering of the station output acts in the same manner, sends a reverse current through the booster field and causes the battery to charge.

If, as cited above, regulation of the generator load within 10 per cent were to be maintained, the output of the counter e.m.f. generator would have to be 10 times that of the energy required for the field excitation of the booster, as but 10 per cent of its voltage is applied for that purpose. If the regulation were to be 5 per cent in either direction, the output of the counter e.m.f. generator

would have to be 20 times that of the energy required for the booster field excitation. The excess output is, of course, not lost, but passes to the line. The maintenance of any fixed load upon the generators in this system is controlled by means of variable shunts around the exciting coil of the counter e.m.f. generator, which carries all the generator output.

The other method of regulating by variations in the generator load is by means of an electromechanical regulator. This regulator consists of two or more groups of carbon discs, connected in the manner of the Wheatstone bridge, with the exciting field coil of the booster connected in the position of the galvanometer. A pivoted lever is so mounted that its movement brings pressure to bear upon one set of the groups and releases it upon the other, so as to change their respective resistance and to vary and reverse current through the field of the exciting coil. To one end of the lever an adjustable spring is attached and to the other end a magnet core influenced by the current in the generator circuit. At the average generator load which is to be maintained, the pull of the magnet is balanced by the pull of the spring at the other end of the lever. Under these conditions the pressure upon the two groups of carbons is the same, and no current flows through the booster field coil. A slight increase of current in the generator circuit is sufficient to cause additional pressure upon one of the groups of carbons compared with the other, and send current to the field regulating coil of the booster in a direction to cause the battery to discharge, which it does to an amount practically equal to the increase of load in the outside circuit, letting only a small portion of the additional load fall upon the generator to effect the regulation. If the generator load is decreased following the decrease in the outside load, the spring becomes stronger than the magnet, and a pressure is put upon the opposite group of carbons, reversing the current through the booster field coils and causing the battery to charge.

It has been found that very close regulation can be maintained in this way, even with a load varying almost instantaneously. Regulation of less than 2 per cent in either direction has been frequently obtained. Complete control of the output of the generators is secured by this system, and the generators can be set to run at any average load desired, by simply varying the strength of the spring opposing the magnet. If the pull of the spring is increased, the generator current is immediately increased to a corresponding degree, as otherwise the battery would charge till the increase of the

generator load would balance the spring pull. The end of the spring carries a pointer, and there is a calibrated scale in amperes by which the generator output can be instantly set at its desired value.

This form of regulator is mounted on a switchboard, and occupies not much more space than the ordinary recording wattmeter. The spring and its indicator, as well as the carbons, are on the front of the board, and the lever extends through the board, and in stations of any considerable size carries a simple horseshoe of soft iron which is hung over the bus-bar carrying the total load of the generators. The usual connection for such a regulator is to have, electrically considered, two groups of carbons. These are connected all in series, and by means of a connection made to the storage battery a small current is maintained through them. At the middle point of the carbons, which is the point where pressure is divided, a lead is taken through the field coil of the booster to the middle point of the battery, to which the two ends of the carbons are connected. In this way, when the pressure on the two groups of carbons is equal and the resistance is, therefore, equal, there is no difference of potential between the midway point of the carbons and the midway point of the battery.

In plants where very large boosters are used it is desirable to magnify the effect of the regulator by means of an exciter connected between the regulator and the booster, rather than to increase the size of the regulator. This regulator has some advantages over any other method of battery regulation, in that it is possible to adjust the sensitiveness of regulation on the charge side of the battery as compared with the discharge, and *vice versa.* For instance, in a generating station or a sub-station with a fluctuating load, it is not necessary or always desirable to maintain the load on the generating machinery absolutely at its ratings but to allow it to share the increased loads to some considerable extent, in order to reduce the discharge rate of the battery. If this is done by any direct means of field-coil regulation it will follow that if the generating apparatus shares a portion of the overload it will also have to share the underloads, or loads below the average, in the same proportion.

With the carbon regulator, on the other hand, by the introduction of a resistance in one of the groups of carbons, the regulation on discharge, for instance, may be made of any degree of sensitiveness, so as to allow the generator machinery to share any portion of the overloads, while on the underloads full sensitiveness of regulation

may be maintained and the load on the generators not allowed to drop off below the average. In this way the battery may be accumulating charge; as it receives more charge than discharge, the actual variation of load on the station is considerably lessened and the maximum output of the generating machinery and the battery is not increased. In this manner the overload capacities of engines, generators, rotary converters, etc., may be utilized to the fullest advantage, and the battery may be discharging at very high rates; but by taking full advantage of every dropping off of the load below a predetermined point sacrifice as little of its capacity as possible, and may assist the generator on the peak of the load, while losing but a minimum of its capacity. Also with this form of regulator, a zone of non-regulation may be created extending say from 10 per cent above and below the average load, whereas for loads above and below this the regulation may be as perfect as possible. This permits of reducing the total amount of charge and discharge in ampere-hours that a battery may receive by a very great amount, while keeping the variation of the load on any system within non-objectionable limits, and the life of the battery may be materially increased, often without reducing any of its benefits.

As to the construction of a battery for railway service, it is pretty well established that the positive plates should be of the "Planté" type and not of the "pasted" type; while the negative plates are preferably of the "pasted" type.

The characteristic trouble of negative plates has been loss of capacity due to shrinkage of the spongy, finely divided, active material into a denser and less porous material. This has particularly been true of "Planté" negative plates, where the active material is relatively small in quantity and has been reduced from the peroxide previously formed from the plate itself. A process has been discovered of manufacturing a negative active material which always retains its loose, spongy, porous condition; but, as this has but little mechanical strength, means have to be provided in the plate for retaining it in position. Such plates have proven eminently satisfactory in service and extended tests show a very greatly increased life and the maintenance of low resistance and low polarization factors.

In considering the life of a positive "Planté" plate, it should be taken into account that the life in ampere-hours of a pound of lead entering into the construction of a positive plate is not governed by the surface development of the lead, but by the means

which have been provided for retaining the active material formed from the plate itself in proper contact with it, and the prevention of the loss of such active material from being washed away or carried away by the gases which rise from the surface of the plate. The extended development of a pound of lead increases the capacity which it would yield on any one discharge, but lessens the total number of discharges available by more than a proportionate amount, a very highly-developed plate yielding less total life in ampere-hours mainly because its mechanical structure and its conductivity are affected to a greater extent by the removal or loss of a portion of the substance of the plate. For this reason the development of the active lead should be made in such a manner that it will provide secure receptacles for the retaining of the active material; and the necessary further corrosion of the active lead for the purpose of replacing active material carried away should not interfere with the mechanical strength or with the conductivity of the plate.

No modern battery installed for railway service should be in danger of a break-down at any rate of discharge that could possibly be imposed upon it, and in well-designed batteries there is absolutely no danger of break-down due to any rate of overload.

Some years ago the electrical engineer was disposed to look upon a storage battery with more or less misgiving. Even at the present time there may be found occasionally an engineer who, not realizing the progress that has been made in this art and the place that the storage battery has established for itself, is disposed to take this skeptical attitude. If, however, the history of the storage battery business for the past 10 years, which period practically covers its entire commercial history, should be compared with the first 10 years of any other electrical apparatus, we believe that the comparison will show a series of complete successes and the absence of anything approaching a failure or setback, that will compare favorably with the history of any other electrical apparatus.

Discussion.

Chairman Duncan: The paper is now open for discussion. I would like to ask Mr. Sprague if the New York Central is going to put in batteries, or if he can say whether they are or not?

Mr. F. J. Sprague: That is a question I cannot answer at present. My experience with storage batteries has been such as to lead me to regard them with favor in some classes of work. On the South Side Ele-

vated road in Chicago, storage batteries were introduced for two reasons, one to help take the sharp fluctuations in load, and the other to provide additional facilities when the demands of the road were growing so rapidly as to run ahead of possible direct equipment. No boosters were used, the batteries responding fairly well automatically to the rise and fall of potential where connected to the line, but varied somewhat in action by cutting in or out an extra feeder.

The New York Central presents a problem which is materially different from that of elevated and suburban roads. Usually on those classes of service there are a large number of units, and the load is fairly distributed. The New York Central has about nine sub-stations, the units weigh from 150 to 700 tons, and the sub-stations are a considerable distance apart. It is impossible to avoid a condition which is emphasized on heavy steam railway work, extreme local variations of load. There will probably be at times as many as four trains supplied almost entirely by one sub-station, while at other times there will not be any load whatever on it. Of course that means a pretty large variation, and sometimes a very rapid one.

Personally, I am strongly in favor of the use of storage batteries in this instance, not only partly to relieve the sub-station machinery and to reduce its capacity; but also to provide a reserve, in case of any accident to the central power plants or transmission system.

The equipment is being laid out with the idea of maintaining train movements from two stations, either of which in emergency can operate the entire service for a reasonable time. I do not think that in the matter of cost, all things considered, there would be much difference between the installation of a plant with or without storage batteries, that is, the saving of central station and sub-stations would be about offset by the cost of batteries and boosters.

ELECTROLYSIS OF UNDERGROUND CONDUCTORS.

BY PROF. GEORGE F. SEVER, *Columbia University.*

In the spring of 1903, Mr. L. B. Stillwell, Mr. F. N. Waterman and the writer felt that it was desirable to compile and coordinate as much information as could be procured on the subject of the electrolysis of underground conductors, due to the operation of electric railways. It was felt that both the opinions regarding electrolysis and the practice in remedying the same were so diverse that it would be of value to collect all this information and present it before the International Electrical Congress. Through the efforts of the first-named gentlemen the practice of the electric street railways was secured, and all the world's literature, which was available, was collected and put into the form of a digest. The writer collected information regarding the attitude of the municipalities, including such ordinances regarding electrolysis as had been put into effect up to that time. The data was put into tabular form by Mr. Waterman, and through the courtesy of both Mr. Stillwell and Mr. Waterman the writer has been able to present the final results before this Congress.

The data is presented in the five tables which are attached hereto.

Table I shows the street railway practice in the United States regarding the use of return feeders and the effect of increasing the capacity of these feeders. The reports are shown from 102 electric railways.

Table II shows the recommendations which have been made to 29 municipalities by city and other engineers. The results of these recommendations are shown in a few cases.

Table III shows the most essential electrical features of the municipal ordinances which are in force in 12 different municipalities. The inconsistencies in some of these ordinances are remarkable, particularly in the cases of Atlantic City and Altoona.

Table IV presents a summary of the opinions of municipal officers as extracted from the letters received from them. Fifty municipalities, widely distributed, were heard from.

Table V presents a summary of expert opinion concerning electrolysis. This expert opinion shows many differences in the recommendations as to remedy. It is the writer's hope that the discussion on this presentation may be full and that some definite conclusions may be arrived at for the betterment of the conditions which are known to exist in some localities.

TAB

SUMMARY OF STREET RAILWAY

Number.	State.	City.	Population served.	Name of electric street railway company.	System of operation.	Date of electrical installation.	Miles of track.	Weight of rails.	Bonding system.	Number and size of bond per joint.	Nature of return feeder system.
1	Ala...	Birmingham	38,400	Birmingham Ry. Lt. & Pw. Co.	......	1894	99	60–88	W. & M..	4–0	None
2	Ala...	Huntsville	8,100	Huntsville Ry. Lt. & Pw. Co.	......	1900	5	60	Copper..	....	None
3	Conn.	Bristol	9,600	B. & P. Ry. Co.	......	1895	8	56–60	Copper..	4–0	None
4	Conn.	Middletown	9,600	M. St. Ry. Co.	......	....	10	60	Copper..	2–0	No. 2 track wire
5	Conn.	Montville	2,400	M. St. Ry. Co.	......	....	13	60	Copper..	2 4–0	None
6	Fla..	Jacksonville	28,500	J. Elec. Co.	......	....	18	45–70	Chase S..	....	1 ret. feeder.
7	Ga...	Athens	10,200	A. Elec. Ry. Co.	......	1895	7	40–60	Protect..	1–0 2–0	None
8	Ga...	Dahlonga	12,000	G. & D. Elec. Ry. Co	......	....	27	70	All wire.	2 2–0	None
9	Ill....	Alton	22,500	A. Ry. Gas & Elec. Co	......	....	12	60–75	....	2 4–0	On all lines..
10	Ill....	Chicago	1,700,000	C. City Ry. Co.	......	....	184	95	Cast weld	....	On all main lines
11	Ill....	Decatur	25,000	D. Tr. & Elec. Co..	......	....	14	60–70	Copper..	2–0	None
12	Ill....	Freeport	13,300	F. Ry. Lt. & Pw. Co	......	....	7	56	Wire....	4–0	Ret. feed....
13	Ill....	Jacksonville	15,100	J. Ry. Co.	......	....	5	40–60	Protect..	4–0	None
14	Ind..	Madison	7,800	M. Lt. & Ry. Co...	......	....	4	56	Wire.....	2–0	None
15	Ind..	Columbus	10,500	J. S. Cramp's Elec. St. Ry	......	....	7	30–86	Wire.....	4	None
16	Ind..	LaFayette	18,100	L. F. St. Ry. Co...	......	....	18	60	A. S.& W.	4–0	On one line..
17	Iowa.	Keokuk	15,000	K. Elec. Ry. & Power Co.	......	....	8	56	Wire....	1–0	None
18	Ky...	Louisville	205,000	L. Ry. Co.	......	....	142	60–100	A. S.& W.	....	½ to 2 miles from P. S..
19	Me...	Bangor	22,000	Penobscot Central Ry. Co.	......	....	27	56	Chase S. protect.	....	None
20	Me...	Calais	8,000	C. St. Ry. Co.	......	....	7	48–56	Chicago protect.	2–0 4–0	Ret. feeds...
21	Me...	Kennebunkport	2,100	Atlantic Shore Line Ry.	......	....	2	60	Brown crown..	....	None
22	Md...	Cumberland	17,100	C. Elec. Ry. Co.	......	....	7	40–73	Copper..	....	No. 2 gr. wire
23	Md...	Hagerstown	18,600	H. Ry. Co.	......	....	14	56–72	Copper..	2–0 4–0	None

LE I.

PRACTICE IN THE UNITED STATES.

Are pipes tapped to rails?	Are pipes tapped to bus?	What area is drained?	No. of power stations.	Maximum current from each.	Minimum line voltage.	Nature of soil.	Nature of corrosion.	Extent of corrosion.	Any claim against railway company?	What remedy applied?	Effect of remedy.
No...	No...	None .	1	......	350	....	....	Some. ...	No.........	None	....
No...	No...	None .	1	300	475	Fav. ...	....	None	No.........	....	....
No...	No...	None .	1	500	600	....	....	Some. ...	No.........	....	....
No...	Yes..	....	1	500	450	....	....	None	No.........	....	....
No...	No...	None .	1	2,500	350	....	....	Some	Yes........	Larger bonds..	No more trouble.
No...	No...	None .	1	700	375	....	....	None	No.........	....	....
No...	No...	None .	1	400	450	Unfav..	....	None	No.........	....	....
No...	No...	None .	1	500	400	....	....	None	No.........	....	....
No...	No...	None .	1	1,200	450	....	....	None	No.........	....	....
No...	Yes..	....	4	12,000	400	....	....	Some. ...	Nothing definite..	None	....
No...	No...	None .	1	2,500	450	Fav....	....	Some. ...	No.........	None	....
No...	No...	None .	1	400	425	....	....	Some. ...	No.........	None	....
No...	No...	None .	1	......	450	....	....	None	Once	Analysis showed rust.	....
Yes..	Yes..	....	1	250	480	....	....	None	No.........	....	....
No...	No...	None .	1.	......	500	Unfav..	....	None	Once.......	Proved earth corrosion.....	....
No...	No...	None .	1	500	450	....	....	None	No.........	....	....
No...	No...	None .	1	500	450	Clay ...	....	None	No.........	....	....
Yes..	Yes..	+	1	10,000	500	....	....	Some	Yes........	Ret. feeds.	Less complaint.
No...	No...	None .	2	......	480	....	....	None	No.........	....	....
Yes..	Yes..	+	1	350	450	....	....	Some	Yes........	Improving return.	Less trouble.
No...	No...	None .	3	1,000	360	....	....	None	No.........	....	....
No...	......	....	..	......	...	....	....	None	No.........	....	....
No...	No...	None .	1	800	350	Fav. at point.	....	At one point..	No.........	None	....

TABLE I —

Number.	State.	City.	Population served.	Name of electric street railway company.	System of operation.	Date of electrical installation.	Miles of track.	Weight of rails.	Bonding system.	Number and size of bond per joint.	Nature of return feeder system.
24	Mass.	Amherst	5,000	A. & S. St. Ry. Co.	......	....	15	60	Copper ..	4-0	Few gr. wires
25	Mass.	Athol	7,100	A. & O. St. Ry.	......	....	7	50–90	....	....	Ret. feed....
26	Mass.	Cottage City	....	C. C. & E. Traction Co	......	....	5	50	....	....	Gr. wire.....
27	Mass.	Conway	1,600	C. Elec. St. Ry. Co.	......	....	6	60	S.V. & B.	....	None ....
28	Mass.	Fitchburg	12,400	F. & L. St. Ry. Co.	......	....	32	70–90	Crown...	4-0	On all lines..
29	Mass.	Gardner	10,000	G. W. & F. St. R. R. Co	......	....	16	45–60	....	1-0 2-0	None ....
30	Mass.	Greenfield	8,000	G. D. & N. St. Ry. Co............. G. & T. F. St. Ry. Co	......	....	23	48–60	....	4-0	None ....
31	Mass.	Holyoke	45,700	Mt. Tom R. R.	......	....	1	...	....	4-0	None ....
32	Mass.	Holyoke	45,700	H. St. Ry. Co.	......	....	43	...	Crown...	4-0	On one line..
33	Mass.	Lowell	653,000	B. & N. U. Ry. Co.	......	....	440	90	....	2 4-0	On nearly all lines. ...
34	Mass.	Maynard	3,100	C. M. & H. St. Ry. Co	......	....	18	60–90	Crown...	....	None ....
35	Mich.	Escanaba	9,500	E. Elec. St. Ry. Co.	......	....	8	45–60	....	....	None ....
36	N. H.	Chester	2,500	C. & D. Ry. Ass'n..	......	....	8	48	....	....	Some ....
37	N. J.	Asbury Park	4,000	A. C. Elec. R. R. Co	......	....	24	60–70	....	2-0	2-0 for each track ......
38	N. J.	Camden	76,000	C. & Sub. Ry. Co.	......	....	67	70–90	....	2 4-0	None ....
39	N. J.	Keyport	3,100	J. C. Traction Co.	......	....	6	65–70	....	.....	....
40	N. J.	Millville	10,600	M. Traction Co.	......	....	12	60	....	....	None ....
41	N. Y.	Albany	....	A. & H. R. R. Co	Third rail.	..	42	80	M. & E..	4-0	None ....
42	N. Y.	Binghamton	60,000	B. Ry. Co	......	....	37	...	....	....	Ret. feed....
43	N. Y.	Canandaigua	6,000	Ont. Lt. & Trac. Co	......	....	3	40	Copper ..	....	Ret. feed....
44	N. Y.	Corning	12,500	C. & P. P. St. Ry..	......	....	6	56–90	Crown...	4-0	None ....
45	N. Y.	Elmira	35,700	E. Wat. Lt. & R. R. Co	......	....	27	50–90	M. & E..	2 4-0	Ret. feed....
46	N. Y.	Fishkill	3,700	Citizen R. R. Lt. & Pw. Co	......	....	7	56	Chicago plastic wire...	....	Ret. feeds...
47	N. Y.	Fredonia	18,500	D. & F. R. R. Co..	......	....	4	48–60	M. & E. O.B.Co.	4-0	....
48	N. Y.	Gloversville	18.000	F. J. & G. R. R...	......	....	19	56–80	Copper ..	2-0	None ....
49	N. Y.	Hornellsville	12,000	H. Elec. Ry. Co....	......	....	5	56	Copper ..	4-0	Ret. feed....

(*Continued*).

Are pipes tapped to rails?	Are pipes tapped to bus?	What area is drained?	No. of power stations.	Maximum current from each.	Minimum line voltage.	Nature of soil.	Nature of corrosion.	Extent of corrosion.	Any claim against railway company?	What remedy applied?	Effect of remedy.
No...	No...	None.	2	600	400	....	....	None	No.........	....	....
No...	Yes..	....	1	......	525	....	....	None	No.........	....	....
No...	No...	None.	1	.....	450	....	....	None	No.........	....	....
No...	No...	None.	2	200	500	....	....	None	No.........	....	....
No...	No...	None.	1	1,700	450	....	....	None	No.........	....	....
No...	.....	Wet places	1	......	...	Sand, lime, clay	....	None	No.........	....	....
+ Area.	No...	None.	4	......	...	....	....	None	No.........	....	....
No...	No...	None.	1	500	390	....	....	None	No.........	....	....
No...	Yes..	....	1	750	375	....	....	None	No.........	....	....
......	Yes..	+	1	3,500	400	....	....	Some	Yes........	Gr. wires......	Reduced P. D.
No...	......	....	1	......	400	....	....	None	No.........	....	....
No...	No...	None.	1	......	550	....	....	None	No.........	....	....
No...	Yes..	....	..	......	...	....	....	None	No.........	....	....
No...	No...	None.	2	1,600	575	....	....	None	No.........	....	....
+ Area	No...	None.	4	......	450	....	....	Little....	Yes........	Investigation..	No more trouble.
No...	No...	None.	2	500 1,000	400	....	....	None	No.........	....	....
No...	No...	None.	1	......	...	....	....	None	No.........	....	....
No...	No...	None.	3	......	400	Clay...	....	None	No.........	....	....
No...	No...	None.	2	......	450	....	....	None	No.........	....	....
No...	Yes..	....	1	150	400	....	....	None	No.........	....	....
No...	No...	None.	1	850	475	Fav. ...	....	None	No.........	....	....
No...	No...	None.	1	......	325	Gravel.	....	On rails..	Yes........	Ret. feed	Economy.
No...	Yes..	....	1	......	500	....	....	Some	Indefinitely....	Ignored it	....
No...	No...	None.	1	800	500	Clay, gravel.	....	Some	No.........	Better bonding	Suppressed.
No...	......	....	3	......	400	Fav....	....	Some	No.........	None	....
No...	......	....	1	......	470	....	....	None	None	....	....

TABLE I—

Number.	State.	City.	Population served.	Name of electric street railway company.	System of operation.	Date of electrical installation.	Miles of track.	Weight of rails.	Bonding system.	Number and size of bond per joint.	Nature of return feeder system.
50	N. Y.	Hoosick	30,000	Ben. H. Valley Ry. Co	......	....	17	60	Plastic wire....	1-0	None ....
51	N. Y.	Huntington	3,000	H. R. R. Co.......	......	....	8	56	....	....	None ....
52	N. Y.	Ithaca	13,000	I. St. Ry. Co......	......	....	8	45-60	Wire	2 1-0	None ....
53	N. Y.	Jamestown......	23,000	J. St. Ry. Co	......	....	21	45-80	....	2-0 3-0	No. 2 to No. 0 gr. wire...
54	N. Y.	Port Chester....	7,500	N. Y. & S. Ry. Co.	......	....	17	80-100	O. B. Co.	2 300-000	None ....
55	N. Y.	Seneca Falls.....	10,500	G. W., S. F., & C. L. Tr. Co........	......	....	18	45-73	Wire	2-0	1-0 ret. feed.
56	N. Y.	Utica	114,000	U. & Mo. Val. Ry. Co	......	....	88	80-90	....	2 250-000	None ....
57	Ohio.	Chillicothe	15,500	C. Elec. St. Ry. & Pw. Co..........	......	....	6	50	Wire	2-0	....
58	Ohio.	Cincinnati	1,400,000	C. L. & A. Elec. St. Ry. Co.........	......	....	42	70	Protect..	....	None ....
59	Ohio.	Cleveland.........	382,000	East O. Tr. Co....	......	....	95	...	....	....	....
60	Ohio.	Columbus	126,000	C. L. & S. Ry. Co. and others.......	......	....	50	70-90	Copper..	....	None ....
61	Ohio.	Dennison	3,800	U. Elec. Co.......	......	....	2	48	Wire	....	....
62	Ohio.	Toledo...........	125,000	T. B. G. & So. Tr. Co	......	....	60	60	Copper..	4-0	None ....
63	Ohio.	Lima	22,000	L. Elec. Ry. & Lt. Co	......	....	12	60-70	Crown...	4-0	Ret. feed ....
64	Ohio.	Lima	22,000	W. O. Ry. Co.....	......	....	47	60-72	Crown...	4-0	None ....
65	Ohio.	East Liverpool..	16,500	U. Pw. Co........	......	....	12	56-82	Copper..	2 4-0	None ....
66	Ohio.	Marion	12,000	M. St. Ry. Co.....	......	....	5	60	Plastic ..	....	Gr. wire at sw ....
67	Pa ...	Copley...........	1,600	C. E. & I. St. Ry. Co	......	....	...	70-80	M. & E..	....	None ....
68	Pa ...	Carlisle..........	9,600	C. & Mt. H. Ry. Co	......	....	6	65	....	3-0	None ....
69	Pa ...	Erie	53,000	E. Elec. Motor Co.	......	....	31	80	Copper..	4-0	None ....
70	Pa ...	....	....	Media, Middletown, A. & C. El. Ry..	......	....	19	70	Copper..	4-0	None ....
71	Pa ...	Harrisburg......	50,000	H. Traction Co....	......	....	49	60-90	....	2 4-0	....
72	Pa ...	Hazleton	14,000	L. Tr. Co.........	......	....	20	56	Plastic wire...	4-0	4-0 ret. feed.
73	Pa ...	Lancaster	41,000	C. Tr. Co.........	......	....	92	60-90	Copper..	....	None ....
74	Pa ...	Lebanon	18,000	L. V. St. Ry......	......	....	24	90	....	4-0	None ....

(*Continued*).

Are pipes tapped to rails?	Are pipes tapped to bus?	What area is drained?	No. of power stations.	Maximum current from each.	Minimum line voltage.	Nature of soil.	Nature of corrosion.	Extent of corrosion.	Any claim against railway company?	What remedy applied?	Effect of remedy.
No...	No...	None .	1	......	350	....	....	None	Yes........	None	....
No...	......	....	1	......	450	....	....	None	....	....	....
No...	No...	None .	1	1,000	350	....	....	One case.	No.........	Renewed bonds..	....
Yes..	Yes..	....	1	2,000	500	....	....	Some	Yes........	....	....
	+ Area.	....	1	......	450	Fav....	....	None	No.........	....	....
No...	No...	None .	1	......	375	....	....	None	No.........	....	....
No...	Yes..	....	5	......	300	....	....	None	No.........	....	....
......	......	....	..	......	500	....	....	None	No.........	....	....
No...	......	....	1	10,000	400	....	....	None	No.........	....	....
......	......	....	2	......	...	....	....	None	No.........	....	....
No...	No...	None .	9	......	400	....	....	None	No.........	....	....
No...	......	....	1	300	500	....	....	None	No.........	....	....
No...	No...	None .	4	800	400	....	....	None	No.........	....	....
No...	Yes..	....	1	1,200	275	....	....	None	No.........	....	....
No...	No...	None .	6	900	525	....	....	None	No.........	....	....
No...	Yes..	....	2	1,000	...	....	....	Some	No.........	....	....
No...	No...	None .	1	500	500	....	....	None	No.........	....	....
No...	No...	None .	1	......	400	Yes....	....	None	No.........	....	....
No...	......	....	1	......	550	....	....	None	No.........	....	....
No...	Yes..	....	1	2,000	400	In some places.	....	Alleged..	Yes........	....	....
......	......	....	1	......	...	....	....	Some	No.........	....	....
Yes..	No...	None .	2	1,300	390	....	....	Some	No.........	Repaired bonds..	No more trouble
No...	No...	None .	2	500	350	Fav....	....	None	No.........	....	....
No...	No...	None .	1	1,800	400	....	....	....	Nothing serious ..	Investigation..	....
No...	No...	None .	1	5,500	...	....	....	None	No.........	....	....

TABLE I—

Number.	State.	City.	Population served.	Name of electric street railway company.	System of operation.	Date of electrical installation.	Miles of track.	Weight of rails.	Bonding system.	Number and size of bond per joint.	Nature of return feeder system.
75	Pa...	Lewistown	4,500	L. & R. Elec. Ry. Co	......	....	6	60–70	....	3-0 4-0	None
76	Pa...	McKeesport	21,000	P. McK. & C. Ry. Co.	......	....	85	70–90	A. S. & W.	4-0	4-0 ret. feed.
77	Pa...	Philadelphia	....	Am. Rys. Co.	......	....	...	60–90	Protect.	4-0	None
78	Pa...	Scranton	102,000	S. Ry. Co.	......	....	77	40–80	Many	....	Ret. feed.
79	Pa...	Philadelphia	....	Rys. Co. General	......	....	50	50–70	....	2 4-0	Ret. feed
80	Tenn.	Bristol	5,000	B. B. L. Ry. Co.	......	....	7	35–60	Copper	1-0	Ret. feed.
81	Tenn.	Chatanooga	32,500	R. T. Co. of C.	......	....	16	60	....	4-0	None
82	Tenn.	Chatanooga.	32,500	C. E. Ry. Co.	......	....	41	45–75	Copper, iron	....	½ mile from P. S.
83	Tenn.	Jackson	14,500	J. & Sub. St. R. R. Co.	......	....	8	60	....	....	Ret. feed.
84	Vt....	Burlington	19,000	M. P. St. Ry. Co.	......	....	5	60	Chicago	....	Gr. wires.
85	Vt....	Springfield	3,500	S. Elec. Ry. Co.	......	....	9	50–60	Crown	....	None
86	Va...	Charlottsville	10,000	C. C. & Sub. Ry. Co.	......	....	4	...	....	....	....
87	Va...	Danville	16,500	D. Ry. & Elec. Co.	......	....	6	90	Protect.	....	None
88	Va...	Lynchburg	28,000	L. Tr. & Lt. Co., R. Ry. & Elec. Co.	......	....	16	45–100	Crown, G. E.	4-0	Ret. feed.
89	W. Va	Parkersburg	20,000	P. M. & I. Ry. Co.	......	....	29	60	Protect.	4-0	None
90	Wis..	Eau Claire	17,500	C. V. Elec. Ry. Co.	......	....	22	45–70	A. S. & W.	4-0	None
91	Wis..	Manitowac	13,500	M. & N. Tr. Co	......	....	...	60	Crown, G. E.	4-0	None
92	Wis..	Merrill	10,300	M. Ry. & Lt. Co.	D'ble trol.	..	2	...	None	....	Metallic
93	Ill....	Champaign	17,000	....	......	....	11	60–70	A. S. & W.	....	....
94	Mass.	Boston	....	Boston Elevated Ry. Co.	......	....	...	54–94	Protect. steel plug	1 4-0 2 4-0 3 4-0	Ret. feeds on a heavy traffic line.

(*Continued*).

Are pipes tapped to rails?	Are pipes tapped to bus?	What area is drained?	No. of power stations.	Maximum current from each.	Minimum line voltage.	Nature of soil.	Nature of corrosion.	Extent of corrosion.	Any claim against railway company?	What remedy applied?	Effect of remedy.
No...	No...	None .	1	600	375	......	......	None	No......	......	......
No...	......	......	2	1,200	450	Fav....	......	None	No......	......	......
......	......	......	..	......	...	......	......	Some	Yes......	Rebond ret. feed	No more trouble.
+ Pipes	Yes..	......	2	2,100	350	......	......	Some	No......	Taps to pipes bonding	No more trouble.
No...	No...	None .	2	......	550	......	......	At two places.	Yes......	Rebond 4-0 C. S.	1-8 volt P. D.
No...	Yes..	......	1	......	450	......	......	None	No......	......	......
Yes..	Yes..	......	1	1,500	400	......	......	Some ...	No......	Repaired poor bonds......	......
No...	No...	None .	2	1,100	450	......	......	None	No......	......	......
......	......	......	1	......	450	......	......	None	No......	......	......
Yes..	Yes..	......	1	......	400	......	......	Some ...	No......	......	......
No...	Yes..	......	2	......	475		......	On rails..	No......	River plates...	Improved power.
......	......	......	..	......	...	......	......	None	No......	......	......
No...	No...	None .	1	450	500	......	......	None	No......	......	......
No...	Yes..	......	1	1,600	600	......	......	None	No......	......	......
No...	Yes..	+	2	600	450	......	......	None	No......	......	......
No...	No...	None .	2	350	450	......	......	Some ...	Yes......	Doubled bond .	No more claims.
No...	......	......	1	500	350	......	......	None	No......	......	......
......	......	......	1	30	500	......	......	......	No......	......	......
Pipes	No...	None .	1	......	550	......	......	None	No......	......	......
No...	No...	None .	8	8,800	400	Fav....	Graphitic	Some ...	Yes......	Heavier return	Reduced danger areas.

TABLE I —

Number.	State.	City.	Population served.	Name of electric street railway company.	System of operation.	Date of electrical installation.	Miles of track.	Weight of rails.	Bonding system.	Number and size of bond per joint.	Nature of return feeder system.
95	Mass.	Middleboro......	6,900	Mid. W. & B. B. St. Ry. Co...........	......	....	30	70	....	2 4–0	500,000 C. M. ret.........
96	N. J.	....	....	Pub. Serv. Corp. of N. J.............	......	....	...	70–107	Cast protect..:.	4–0	Ret. feed....
97	N. Y.	Buffalo..........	....	International Ry. Co.	......	....	...	..	....	....	....
98	Ohio.	Columbus.	125,500	C. Ry. & Lt. Co...	......	....	106	40–107	Copper..	....	Ret. feed....
99	Ohio.	Newark	....	C. B. L. & N. Tr. Co	......	....	...	70	....	4–0	None ....
100	S. C.	Columbia.	21,000	C. El. St. Ry. Lt. & Pw. Co........	......	....	14	48–60	Roebling	2–0	3 ret. feed...
101	Tenn.	Knoxville	32,700	K. Tr. Co..........	......	....	24	40–100	Copper..	4–0	....
102	Wis..	Madison.	....	M. Tr. Co........	......	....	...	50–55	....	1–0	None ....

(*Concluded*).

Are pipes tapped to rails?	Are pipes tapped to bus?	What area is drained?	No. of power stations.	Maximum current from each.	Minimum line voltage.	Nature of soil.	Nature of corrosion.	Extent of corrosion.	Any claim against railway company?	What remedy applied?	Effect of remedy.
......	No...	None.	2	500	400	Gravel, sand.	....	None....	No.........	....	....
No...	No...	None.	6	......	...	....	....	None....	No.........	....	....
......	......	....	..	......	...	....	....	None....	....	....	....
......	......	....	2	3,000	400	....	....	None....	Some......	None..........	....
No...	Yes..	....	4	1,500	450	....	....	None....	No.........	....	....
No...	No...	None.	1	1,400	400	....	....	None....	Yes........	None..........	....
No...	No...	None.	2	1,500	400	Fav....	Due to soil....	Some....	Yes........	Improved bonds..	Considerable improvem't.
Pipes	Yes..	....	1	800	450	....	....	Some....	Yes........	Tap pipes to station.......	No more trouble.

TAB

SUMMARY OF MUNICIPAL

Number.	State.	City.	Date.	Report to.	Report by.	Was electrolysis alleged?	What pipes were affected?	Was electric railway company blamed?
1	Conn .	Hartford....	1901	Council	Water Comm'rs.......	Yes..	Water .	Yes..
2	Conn .	Middletown..	1902	Water Comm'r......	....	Yes..	Water .	Yes..
3	Ill	Peoria.......	1898	....	....	Yes..	Water .	Yes..
4	Ind....	Indianapolis.	1901	....	....	Yes..	....	......
5	Ky ...	Newport	1902	City	Water Works Com....	Yes..	Water .	Yes..
6	Md....	Baltimore ...	1901	....	Ch. Eng. Elec. Com...	Some	....	Yes..
7	Mass..	Chelsea	1902	City	Water Comm'rs.......	Yes..	Water .	Yes..
8	Mass..	Worcester ..	1901	....	City Engineer.........	No...	....	......
9	Mich .	Detroit......	1896	Bd. Water Comm'rs.	City Engineer.........	Yes..	Water .	Yes..
10	Minn..	Minneapolis .	1901	....	City Engineer.........	Little	Gas....	......
11	Minn..	St. Paul......	1901	Water Comm'r.....	D. B. Maury, G. H. Benzenburg & Co....	Yes..	Water, gas ..	Yes..
12	Minn..	St. Paul......	1903	City.................	Water Comm'rs	Yes..	Water	Yes..
13	Mo....	St. Joseph...	1894	....	City Electrician	Yes..	....	......
14	Mo....	St. Louis	1903	Water Department.	E. E. Brownell	Yes..	Water, gas ..	Yes..
15	N. J ..	Newark......	1901	....	Engineer Water Dept.	No...	....	......
16	N. Y..	Albany	1901	....	Supt. Bur. of Water..	1893..	Water .	Yes..
17	N. Y..	Buffalo.......	1901	....	Chief Engineer	No...	....	......
18	N. Y..	Rochester ...	1901	Com. Public Works..	E. A. Fisher..........	Yes..	Water .	Yes..
19	Ohio..	Cincinnati ...	1899	Am. Soc. Mun. Im...	Com. Water Works...	No...	....	......
20	Ohio..	Cleveland....	1899	....	Supt. Water Works...	Yes..	Water .	Yes..
21	Ohio..	Columbus....	....	Public Works.......	F. C. Caldwell	......	....	......
22	Ohio..	Dayton.......	1899	....	....	......	....	......
23	Pa	Philadelphia.	1899	....	Ch. Elec. Bureau	No...	....	......
24	Pa	Reading.....	1900	Water Com..........	A. A. Knudson	Yes..	Water .	Yes..
25	R. I ..	Pawtucket ..	....	City Engineers......	A. A. Knudson	Yes..	Water .	Yes..
26	R. I ..	Providence .	1900	Com. Public Works.	A. A. Knudson	Yes..	Water .	Yes..
27	Wis ..	Madison	1899	....	City Water Works	Yes..	Water .	Yes..
28	Wis ..	Racine	....	....	G. H. Benzenburg	Yes..	Water .	......
29	Va....	Richmond...	1899	Supt. Water Works.	A. Schoen	Yes..	Water .	Yes..

LE II.

REPORTS ON ELECTROLYSIS.

What remedy suggested?	What remedy applied?	Result of improvement.	Was legal action instigated?	Plaintiff.
Double trolley.........	....	....	......	....
Better return.........	Rebonding	No more trouble.. ...	......	....
Double trolley...	....	....	Yes..	Peoria Water Co.
....	....	....	......	....
....	....	....	......	....
Efficient bonds........	....	....	......	....
....	....	....	......	....
....	....	....	......	....
Efficient return.......	Return feeders........	Reduced P. D.'s.......	......	....
....	....	....	......	....
....	....	....	......	....
....	....	....	......	....
....	....	....	......	....
Good return...........	....	....	......	....
....	....	....	......	....
Return feeders........	+ Drainage	No more trouble......	......	....
....	....	....	......	....
Better return.........	Better return.........	Reduced P. D.'s.......	......	....
....	....	....	......	....
....	....	....	......	....
Efficient return.......	....	....	......	....
....	....	....	Yes..	....
....	Efficient return drainage..................	....	......	....
Efficient return, double trolley.......	....	....	......	....
Double trolley.........	....	....	......	....
Efficient return.......	....	....	......	....
....	Connected track and pipes	No improvement......	......	....
....	....	....	......	....
Double trolley.........	....	....	Yes..	....

TAB

SUMMARY OF MUNICIPAL ORDINANCES

Number.	State.	City.	Date.	Immediate cause for ordinance.	System required.	Are taps from pipes to rails allowed?	Is drainage in + area allowed?	Is drainage in other area allowed?
1	Conn ..	Montville..........	....	....	....	....	....	....
2	D. C...	Washington	....	....	Double trolley or equivalent..........	....	....	....
3	Ill......	Chicago.	1900	....	....	....	....	....
4	Ill......	Freeport...........	....	Franchise	....	....	....	....
5	Ga......	Atlanta............	1898	....	....	....	....	....
6	Mass...	Fitchburg..........	....	....	....	....	....	....
7	Mich ...	Battle Creek	....	....	Double trolley if demanded	No.	....	....
8	N. J....	Atlantic City......	1902	....	....	No.	No.	No.
9	N. Y...	N Y. city	....	....	....	....	....	....
10	Pa......	Altoona	1902	....	....	....	....	....
11	Pa	Philadelphia.......	....	....	....	....	....	....
12	Va.....	Richmond.........	1896	....	....	....	....	....

LE III.

CONCERNING ELECTROLYSIS.

Is railway company made liable for corrosion?	Maximum + P. D. pipes to rails.	Maximum — P. D. pipes to rails.	Allowable leakage of current.	Drop allowed in return.	Drop per mile allowed in return.	Remarks.
....	....	....	....	....	....	Capacity of return not less than + feeders.
....	....	....	....	....	....	....
....	1	1	....	½-300′	8.8	....
All damage to water and gas pipes	....	....	....	....	....	....
....	....	....	No leakage.........	....	....	....
For all damage ...	....	....	....	....	....	....
....	¼	¼	No more than one amp. in any pipe.	⅛-200′	3.3	....
Yes..............	¼	¼	No leakage.........	¼-200′	6.6	....
....	....	....	....	25	....	Electric code of city department.
Yes..............	....	....	No leakage.........	....	....	Periodic tests and excavations.
....	¼	¼	....	⅛-200′	3.3	....
Yes..............	....	....	....	....	....	....

TABLE IV.

SUMMARY OF MUNICIPAL LETTERS CONCERNING ELECTROLYSIS IN JUNE, 1903.

Number.	State.	City.	Information received from.	Report concerning electrolysis.	Report concerning electrolytic survey.	Are water pipes owned by city?	Remarks.
1	Ala......	Birmingham .	City Engineer..........	None	....	.....	....
2	Ala......	Montgomery .	Mayor....................	None	....	.....	Investigation being made by City Elec. Report, October, 1903.
3	Cal......	Oakland......	Secretary to Mayor....	None	....	.....	....
4	Col......	Denver........	Secretary to Mayor....	None	....	.....	....
5	Conn. ..	Bridgport	Mayor.	None	....	No..	....
6	Conn....	Hartford	Mayor	....	....	.....	President Water Board reports "but little damage"
7	Conn....	Waterbury ...	Mayor	None	....	.....	....
8	Del.	Wilmington...	City Clerk..............	Only from Water Dep't..	....	.....	....
9	D. C. ...	Washington..	Electric Engineer......	1898–9, 1900	Yes....................................	.....	....
10	Ga.	Atlanta	City Electrician........	None	....	.....	....
11	Ind......	Fort Wayne..	Mayor	None	....	.....	Railway company to take care of all damage.
12	Ind......	South Bend...	Mayor	None	....	.....	....
13	Iowa	CouncilBluffs.	Mayor	None	....	.....	....
14	Iowa....	Dubuque	Mayor	None	None	.....	....
15	Ky..	Covington....	Supt. Water Works ...	None	....	.....	....
16	La.	New Orleans..	Secretary to Mayor	None	Has received some attention.	.....	"We do not believe damage was serious."
17	Me.	Portland......	Com. Pub. Works......	None	....	.....	"We have had very little trouble."
18	Md......	Baltimore.....	Chief Engineer.........	None	....	.....	"Few complaints." "The trouble is generally local."
19	Mass.. ..	Cambridge ...	City Electrician........	Report by C. H. Morse...	....	.....	....
20	Mass. ...	Holyoke......	City Engineer..........	None	....	.....	"No trouble whatever."
21	Mass. ...	Lawrence	Supt. Water Board.....	None	....	.....	"We have not been troubled in any way."
22	Mass. ...	Lynn.........	Clerk	None	....	.....	....
23	Mass. ...	Malden........	Clerk	None	....	.....	....
24	Mass....	New Bedford.	Mayor	None	Now investigating	.....	"As far as we know none of our water piping has been damaged to any great extent."

25	Mass.	Newton	City Engineer	By Stone & Webster, 1895.	.....	.....	"Up to present time, there has been little or no complaint." Gas company installed insulating joints.
26	Mass.	Springfield	Mayor	None	.....	.....	"Little complaint of it, but none of importance."
27	Mich.	Bay City	Mayor	A. A. Knudson, 1902	.....	.....	Report not printed.
28	Mich.	Grand Rapids.	Mayor's Secretary	None	.....	.....	.....
29	Minn.	Duluth	Mayor	None	.....	.....	"We have none." "We have never been bothered."
30	Mo.	St. Joseph	Mayor	None	.....	.....	.....
31	N. H.	Manchester	Mayor	None	.....	.....	"Manchester has never suffered annoyance."
32	N. J.	Bayonne	Secretary to Mayor	None	.....	.....	.....
33	N. J.	Elizabeth	Mayor	None	.....	.....	"Have had but few complaints."
34	N. Y.	Buffalo	Dep. Water Comm'r.	Report of deputy, 1902	.....	.....	"I have not found a leak." (From electrolysis.)
35	N. Y.	Troy	City Engineer	.....	.....	.....	"We have not been seriously troubled."
36	N. Y.	Utica	Mayor	None	.....	.....	.....
37	Ohio	Canton	Sec. Water Works	None	.....	.....	"We have had but very slight trouble."
38	Ohio	Cincinnati	City Electrician	None	.....	.....	"It is a condition unknown in this city."
39	Ohio	Cleveland	City Clerk	Water Works Report	.....	.....	.....
40	Ohio	Columbus	Sec. Bd. Pub. Service	Water Works Rep't, 1901.	F. C. Caldwell	.....	Franchises specify "double trolley or equivalent."
41	Ohio	Toledo	Mayor	None	.....	.....	.....
42	Pa.	Lancaster	Mayor	None	.....	.....	.....
43	Pa.	Williamsport.	City Engineer	None	.....	No.	Have noticed spongy or porous pipes.
44	R. I.	Providence	Com. Dep. Pub. Works.	A. A. Knudson	.....	.....	Railway companies "have taken such steps to prevent electrolysis as best they can and continue to use the single trolley system."
45	Tenn.	Memphis	Mayor	None	.....	.....	.....
46	Tenn.	Nashville.	Secretary to Mayor	None	Now investigating	.....	Suit v. Railway Company just entered by gas company.
47	Va.	Norfolk	Supt. Water Dep't	A. A. Knudson	.....	.....	.....
48	Wash.	Seattle	City Engineer	None	Now investigating	.....	.....
49	W. Va.	Wheeling	Mayor	None	.....	.....	.....
50	Wis.	Milwaukee	Ass't City Engineer.	None	"No systematic survey."	.....	.....

TAB

SUMMARY OF EXPERT OPINION

Number.	Name of expert.	Title of article.	Where published.	Date.	Can electrolysis be sufficiently mitigated with single trolley system?	Most suitable remedy.
1	A. V. Abbott....	Electrol. from Ry. Cur..	Cassiers' Mag.......	1899	Yes....	....
2	Baylis...........	Electrolysis	Canadian Elec. Assn.	1894	No.....	Only cure is double trolley..
3	Wm. Brophy....	Prevention of Electrol..	Insurance Eng'r'g...	....	Yes....	....
4	H. P. Brown	Remedy for Electrol....	....	1895	....	Neg. booster.....
5	Ellicott	....	Report in Chicago ..	....	....	....
6	I. H. Farnham ..	....	Cassiers' Mag.......	1895	Yes....	....
7	Fisher...........	Legal Status		1894	....	....
8	A. B. Herrick ...	....	....	....	Yes....	Eff. return.......
9	D. C. Jackson....	Electrol. of Iron Pipes..	Street Ry. Jour......	1894	....	....
10	"	Corrosion of Iron Pipes.	"	1894	Yes....	....
11	Kalsey...........	....	Report to Salt Lake City	....	....	....
12	H. R. Keithley ..	How to Prevent Electrol.	Street Ry. Review ..	1894	No.....	Complete metal circuit ....
13	A. A. Knudson...	Corros. of Metal by Elec.	Amer. Elec-ch. Soc..	1903	No.....	Double trolley...
14	G. Low..........	Rail Bonding & Elec. Corros..............	....	1895	....	....
15	M. R. McAddo...	....	....	....	....	....
16	W. H. Merrill....	Electrol. of Buried Pipes	Western Electric....	1896	Yes....	Double trolley + drainage.......
17	C. H. Morse	Electrol. of Water Pipes	Street Ry. Review ..	....	No.....	....
18	O'Reilly	....	Report to St. Louis..	1896	....	....
19	Parshall	Electrolysis..............	Jour. Inst. of E. Es..	1898	Yes....	....
20	J. Swinburne....	Electrol. of Gas Mains..	Incor. Gas Inst. Eng.	1902	....	....
21	Stone & Webster	Rochester Report.......	....	1901	....	....
22	H. C. Townsend..	....	Cassiers' Mag........	1895	....	Double trolley...
23	....	Results of Electrol......	Boston Report	1895	Yes....	....
24	....	More About Electrol....	Street Ry. Review ..	1893	Yes....	....
25	....	How to Cure Electrol...	Street Ry. Review ..	1894	Yes....	....

LE V.

CONCERNING ELECTROLYSIS.

Requirements as to track construction.	Requirements as to bonding system.	Requirements as to return feeder system.	Are taps from rails to pipes recommended?	Is drainage in + area recommended?	Is drainage in other area recomended?	Are electric railway companies legally liable?	Remarks.
Good	Good	Substantial		Yes			
Good	Good						
Good	Good			No			Suggests insulating pipe joints.
			Yes				
Good	Good		No	Yes	No		Suggests balanced feeder system.
						Yes	
Good	Good						
			+ Area				
		Along entire tracks	Yes				
							Advises good bonding for comp. met. cir.
Good	Good			Yes			
Good	Good	Good		Yes			
				Yes			
				Yes			
			With precaution				Almost no trouble in St. Louis.
Good	Good		No	Yes			
Good	Good			Yes			
				Yes			
						Yes	
				Yes			
Good	Good	Good	Yes				
Good	Good	Good		Yes			

DISCUSSION.

Mr. JOHN HESKETH: Being in the position of having had experience on both sides of the problem I have had reason to give the question very close study. There are certain well-defined lines and conclusions from which I think we cannot escape. To begin with, the onus of protecting underground works from electrolysis or from damage by tramway systems cannot possibly be considered as resting on one or the other party exclusively. It must, if it is to be a successful work, be a mutual one. It is impossible for the telephone company, even by the adoption of all known reasonable methods, to protect their works if the tramway company, on their part, neglect well-known methods. Further, it is impossible for the tramway company to so run their system as to avoid damage, if the telephone company or others interested are laying their works in an unnecessarily dangerous manner. As an instance: In one case which I have in mind, a water company laid its lead service pipes within six inches of the rails of a tramway system. They invited electrolysis; they got it; and then they complained. Further, there are conditions which are easily imaginable, where a system of water pipes acts as a feeder from the zone in which danger is existent to a zone which otherwise would not be dangerous. In such cases the water-supply company, or the gas company, should so insulate its pipes as to prevent the feeding of danger from the one zone into the other. Further, it has been the effort in one or two places to prevent damage by laying down hard and fast rules as to the drop in the return circuit. For instance, the Board of Trade of London laid down an arbitrary figure of seven volts as the maximum difference of potential between the ends of the return. But any figure of drop in the return must take into consideration the length of the line. It is not necessarily the drop along the return that does the damage. It is rather the difference of potential between the return and the other metal bodies in the neighborhood; and yet not altogether so. It is not the difference of potential only, but the capacity for current carrying from the return into the pipe. There may be a huge difference of potential and yet no passage of current into the pipe. There may be a very small difference of potential, and yet a very dangerous current. There we strike another main principle — the method of testing for possible danger, which ought to be clearly defined. It is not sufficient to measure the difference of potential between the pipe and the return. I rather incline to the belief that the method which has during the past year been suggested in Germany, of measuring the difference of potential between the rail and the earth nearest to the rail, is a more correct method. It takes into account the electrolyte between the two bodies.

Recently the Australian Government met in conference the engineers of the telegraph department and engineers representing electric supply industries. In conference, we agreed on certain regulations for the protection of the works of the Postmaster-General of Australia, and the points just mentioned were the salient points brought out in the discussion on the question of electrolysis. When I heard that this Congress was to be held, it appeared to me as rather desirable that an effort be made to

have an expression of opinion from the technical associations of different nations on this most important subjejct, and I mention that now for your consideration, if deemed advisable. It is rather a problem as to how such an expression of opinion could be obtained, but it seems to me, in view of the diversity of regulations throughout the world and the lack of authoritative statements based on a scientific principle, that such a statement prepared by scientific bodies would be invaluable to both sides.

Prof. F. C. Caldwell: In Columbus, Ohio, as has been mentioned by Prof. Sever, we have made some investigation of this matter, and our conditions there are particularly favorable for absence from the trouble. I believe the soil there is not such as to produce much electrolysis, and the lay of the railway system is particularly favorable for freedom from it. It seems to me there are two points upon which definite information is needed in connection with this matter of electrolysis. The first is whether we should look for trouble only where the current leaves to go to other metallic structures, or whether we are to look also to the joints of the pipes. There is much difference of opinion upon this question. It has been claimed that trouble has been found at the joints, but on the other hand we find engineers taking very decidedly the stand that all that is necessary is to keep the current from leaving the pipes and going to other conducting material. Information on this subject would certainly be very valuable. The second point is as to how much current can be allowed in the pipes or to leave the pipes. This is especially important if it is true that we are to look for trouble at the joints. If we must keep the current out of the pipes practically altogether, then it becomes an important matter to know how much current can be allowed to flow and still not add an appreciable amount to their disintegration. There has been a little data along this line published in regard to the resistance of pipes. What is needed is data as to the resistance in the case of pipes laid in dry sandy soil. Where a pipe is laid through a street, if we make an attempt to measure its resistance we shall get the joint resistance of the pipe, the surrounding soil, and other conducting material, so that we cannot be sure that the resistance we get would show the current going through the pipe.

The other question as to how much damage is to be expected from the current when it leaves the pipe, I believe, depends very much upon the surrounding soil. In some cities much more damage may be anticipated, with the same current flowing, than in others. We have been carrying on, at the Ohio State University, some investigation along this line, obtaining earth from different cities and using an electrode which was weighed before and after the test. Our results so far have not been sufficient to warrant any conclusions, but they are interesting. We have found in two different tests a considerable difference in the amount of material in different cities. Soil from Dayton, Ohio, where there has been much trouble, gave a large amount of electrolysis, while that from Columbus gave a very small amount. It looks as if this was an important point to be considered.

Mr. H. E. Harrison: It does not matter practically how much current or what current density flows into a pipe. It has been assumed that the

current flowing into the pipe would come out more or less uniformly through the whole service; but I do not believe this is so. The pipe may pass through a considerable length of soil which will be a very fair insulator, and will then come upon a patch of soil that is conductive to a high degree, with the result that the current density is more visible and the damage greater.

Prof. SEVER: The data which we have collected contains many references to underground conductors other than piping systems, so that I think it is perfectly proper that that phase of the situation should be brought before this meeting. About two years ago, when I became connected with the city government of New York, Mr. Jones brought me a cable sheath which he claimed had been destroyed by electrolysis. I know that on some cable sheaths in New York city, both on the telephone and the power circuits, there are large currents coming presumably from the operation of the electric railways. In the Bronx there has been considerable difficulty. In the borough of Manhattan there has been difficulty which to some extent has been remedied by the co-operation of the officials of the railway company and the telephone companies. I know of one instance where the sheaths were bonded at one point by a heavy copper conductor to a return of the Manhattan "L,"— approximately 1500 amperes passed over that wire — sufficient to heat it so one could not put his hand upon it. The Manhattan elevated road uses its structure completely bonded, its service rails completely bonded, and a large amount of return feeder, something like six or seven million circular mils, to get their current back without causing trouble to their own and other conductors. In spite of all their precautions, there are still thousands of amperes coming back on their cable sheaths as well as those of other companies. It has been drawn to the attention of the city officials for their recommendation, as there are at times a higher potential than twenty-five volts between the end of the line and the nearest sub-station, which is the maximum fixed by the city rules.

Mr. P. B. DELANY: It seems to me there is one phase of this subject which has been overlooked, and that is the shunting of water and gas pipes or the cable sheath, by the grounding of telegraph wires in the city. This may, to a certain degree, account for the apparent discrepancies electrolytically, in different cities and towns and through different soils. We all know that there is in many places a very great leakage — what we call stray or vagrant currents — into the telegraph circuits by way of the ground return. I myself have had experience with wires about a hundred miles in length, and it was rather a disagreeable experience. I tried some synchronous experiments four years ago, and I found there was a voltage varying from three or four volts to seventy-five in that circuit — not constantly, but running up and down. If it had been constant, we might have been able to do something with it, but as it was fluctuating, it was rather disastrous to the experiments at the time. It has occurred to me that in cities where there are hundreds of ground connections made at different points to the pipes and where considerable electric energy is used in the operation of telegraph lines grounded in cities, some of the electrolysis may be even due to that source, as well as

the protection of the pipes from power leakage by the shunting. I think this suggestion may throw some light on the subject, although I presume that this phase of the case has been taken into consideration by Mr. Sever and his associates. It has not been referred to in the discussion.

Mr. BANCROFT GHERARDI: One of the functions of my department is taking precautions against electrolysis trouble on our cables, and in that connection the bulk of our work has been in Brooklyn, on account of our very large underground plant there and the great extent of the overhead trolley system. It is not unusual for us to have to take care of currents as great as 200 or 300 amperes at a single point on our system. This shows that the aggregate amount of current that our system is carrying back to the power-houses amounts to thousands of amperes. There is a certain expense in connection with this work which is quite appreciable, and there still remains, after everything is done that we can do, a certain amount of trouble which is real trouble. The discussion of the responsibility for such trouble and expense is one that it seems to me is beyond the scope of this section and I shall not touch on it here.

Prof. SEVER: In connection with the situation on the Virginia Passenger & Power Company, at Richmond, Va., Mr. Stillwell went at the matter in an engineering way by laying out very carefully on paper the whole railroad system, placing the cars in accordance with their various schedules, and ascertaining those points to which he could most profitably connect a return conductor. He decided upon four points about the city, almost at the corners of a rectangle, and carried directly back to the power station very heavy return feeders, as well as heavily bonding the tracks. From the results which they are getting, it would seem that that is a very satisfactory way in that particular locality to solve the problem. Chemical analyses were made also of the soils. I learned from him a short time ago that the city, through its engineering staff, approved of this scheme and accepted the efforts on the part of the railroad company as an expression of a desire to reduce the trouble. As stated in one of the tables which is presented, the city of Richmond insists that the railroad company must pay for all damage to pipes. How two men are going to agree as to whether damage is due to electrolysis or to ordinary tubercular action or rust, I do not know, and I do not know anybody who does know definitely. The other day we took up in Brooklyn cast-iron water pipes, which had been down fifty-two years, so filled with tubercular nodules that the area of the pipe was reduced to about one-half of its original area. In other places we took up lead pipe, part of which had entirely disappeared, undoubtedly through electrolytic action.

Mr. J. SIGFRID EDSTRÖM: We have had very little trouble in Europe from electrolysis. There has been some, however, in the earliest railroads built in England, but lately we have experienced hardly any trouble. I think this is owing to the very solid construction in bonding and in cables carrying return current to the central station. In Berlin the city officials require that there shall be no larger voltage between any two points of the rails in the city system than two volts — that is, between any points in the rail system of the tramway there must be no greater pressure than two volts. This, or a similar stipulation, has been adopted by many other

cities, including cities in Switzerland and Sweden, where I have had the pleasure to be a railway engineer. In these places we bond the rails with two heavy copper wires at each joint. We have double track generally, and consequently we have eight copper wires at each double pair of joints of the rails. We bond the rails between each other and also the tracks at certain distances. At crossing of bridges or water pipes, where the rails get close to iron in the earth, we insulate the rail with asphalt as much as possible. The rails themselves in the street are generally insulated through a layer of stones or concrete put under the rails. To take the current from the rail, we put it in an *insulated* cable of very heavy dimensions. It is very important to have the cable insulated, as a *bare* copper cable, which I know is often used and which generally is buried deep into the street, invites the current to seek other ways home. The general practice in Europe is that, where a feeding cable is connected to a certain part of the overhead wires, a return insulated cable of the same dimensions as the feeding cable is used. This has also the advantage that in case the positive cable becomes damaged, we can easily exchange it for the return cable until the positive cable has been repaired. All the negative returns are carried into the station through resistances, and these are regulated so that the actual current for which the cable is assigned arrives there; thus the current is split up and no cable is overloaded. In this way every feeding point becomes a "central station." These central stations are planted around in the city, and we have no long flows of current running through the city. Street railways built ten years ago in this way have given no trouble whatever.

As to disturbances on telephones in cities, where the telephones use the earth as a return, there has been some slight disturbance, as naturally a portion of the street-car current must go through the earth and thus some of it also through the telephone wires. In cities where we have a double-wire telephone system, there is no trouble whatsoever.

Mr. HESKETH: Although, as you stated, the regulations define the drop in voltage, I should like to ask what in actual practice is found to be the approximation to the regulation? How closely in Berlin do they comply with the regulations? It would be interesting to know, for the purposes of comparison simply, some of the leading dimensions of the system on which the regulations mentioned are found practicable — the mileage of track and the number of amperes output from the station per mile of track.

Mr. EDSTRÖM: I am here not loaded with figures, but I will try to give part of the information. When the plant is laid out, it is laid out according to a certain schedule, and consequently you know the loads on the several points of the city. According to this the dimensions of the cables are figured out. The track itself has the ordinary two heavy copper wires at each rail and four rails at the side of each other are considered to be sufficient for the two volts drop that should be the maximum in the city. Actual tests have not been taken, so far as I know. I have myself been opposed to the two volt requirement, as I consider this limit very low, and I do not think that on any day of heavy traffic — for instance, Sundays or Easterdays or Whitsundays — that the two volts will be the limit, but that you will actually find the drop far larger.

CHAIRMAN JONES: I perhaps might give you a few salient facts of the effect of electrolysis upon the Postal Telegraph. The Postal Telegraph Cable Company would be only too glad to submit any of the data it has upon the subject of destruction of their cables by electrolysis to Prof Sever for the purposes of his paper. I think they would do this in the interest of electrical engineers everywhere, and in the interest of municipalities whose pipes are being eaten up, and also our good neighbors, the telephone people, who are in the same boat with us in that respect.

I can only, of course, as intimated, speak in a general way on the subject. The telegraph companies were urged to place their wires underground, commencing about the year 1880. Cities got tired of the crow's nests and networks of wires which were in their streets. Some of them were curiosities. Commencing with New York, Philadelphia, and other cities, the agitation became so great that eventually they started to put in their wires underground. As a rule, the cables of the telegraph company are not to be compared with the network of water pipes and gas pipes of cities, nor, except in a few cases, the rails of the tramways. The telegraph companies coming into a city and passing through generally follow a line of pipes, and lately the line of rails of the electric railroads, and we have had a great deal of trouble from electrolysis, in times past, in various cities, commencing with Boston, Hartford, Baltimore, Chicago, Atlanta, New Orleans, and other places. In almost all those places, our cables, that had been laid parallel with or near to the electric railroads, have been attacked, and sections have been eaten up, and our service stopped. We were helpless in the matter, because the cities in some cases had ordered us underground, and after having gone underground, our poles were taken down, and it was not possible to place the poles up again and put the wires on them very expeditiously; so we had to suffer and so the public had to suffer. Its telegrams could not be forwarded until we had made the repairs. We found out, however, that by applying the now universal remedy of bonding, where we could secure a good return wire from the point at which the currents were leaving our cable sheaths to get back to the negative brush of the generating station of the railroad companies, we were rendered entirely immune. We have not had any trouble since we have been properly bonded in any city. Quite recently, in New Orleans, our cable was attacked at one point; but we have since bonded and I think there will be no further trouble. In Hartford we have for some years been bonded, and no trouble has arisen there. In all other places where we have been properly bonded there has been no trouble. It of course follows that the currents which are carried through the trolley pole and down into the motor of the car and so into the rails, is seeking its way back to the generating station, and if the resistance is very high between the point where the car is resting upon the tracks and the negative brush of the machine at the station, it is going to seek a great many ways to get back. It will go all around and follow every route that is possible. As a matter of fact, we loan the sheaths of our cables to the railroad companies to allow them to get their current back to the station, and we bond our sheath to their return wire so they can have every use of it and get back the easiest way possible. We do that to prevent getting hurt.

It is not where their current comes on and starts in to go back that we suffer, but it is where the current leaves our sheath to go through moist ground or some electrolyte to reach the metallic conductor at the power station; so that we have found it was necessary for us to make that path just as good as possible. Our sheaths are one-eighth of an inch lead with 10 per cent of tin, and we have not yet had a case where the carrying capacity has been exceeded by the amount of current that our friends, the railroad people, want to have us carry back for them. It is lying there, doing us no good at all, and we feel no effect from any induction in that respect, and we are glad enough not to be eaten up in the undertaking.

It is pretty difficult to tell whether there is any serious electrolysis generated by telegraph currents or not. Of course, the companies are using much more current now than ever before, on account of their increased business, but prior to the time of electric lights and trolley systems, I have never yet heard of any electrolysis arising from telegraph currents, and do not think they are of sufficient quantity to figure in the case at all.

There is another question, in regard to alternating currents being used for transportation or trolley purposes. How are we going to be effected when alternating currents are used? That is an open question which I am not prepared to discuss, but I would like to call it to your attention.

BRAKING HIGH-SPEED TRAINS.

BY R. A. PARKE.

During a hearing upon an application for a charter for the New York & Port Chester Railroad Company, before the New York Railroad Commission, some three and one-half years ago, the writer was called upon for expert testimony concerning the distance in which electric trains might be stopped, in regular service, from a speed of about 60 miles an hour. It was then that expression was first publicly given to the opinion that the special conditions under which the brakes are applied upon trains of such high speeds warrant a force and promptness of application which could be employed at low speeds only with serious shock and danger of train rupture. For years prior to that time, the uniform teaching and recommendation of The Westinghouse Air Brake Company, as given in instruction cars and by authorized representatives of the company, had been emphatically opposed to the use of what is commonly known as the "emergency application" of the quick-action air brake in ordinary train service, and a proposition which contemplated the use of the emergency application of the quick-action air brake, and particularly the more powerful high-speed form of air brake, appeared to the average railroad officer as nothing short of heresy. Members of the Railroad Commission promptly instituted a line of questioning which made it quite evident that they were similarly impressed.

One of the fundamental grounds upon which the New York & Port Chester Railroad sought to justify the granting of a charter for a railroad line paralleling a steam railroad already in operation, was the materially improved local express-train service which it was proposed to attain through the superior rate of acceleration acquired upon electric trains by the use of the system of multiple control of motors operating upon the axles throughout the train, and the higher rate of retardation to be obtained through the high efficiency of the emergency application of the air brake, in bringing such trains to a station stop.

In presenting the matter to the Railroad Commission, elaborately arranged curves, indicating the rates of acceleration and retardation, had been prepared by the able engineer, Mr. C. O. Mailloux, which appeared to justify the claims for the improved character of train services contemplated by the company. Although multiple-control systems of electrical train control were, at the time, in successful operation, it did not appear that the rate of retardation indicated by the stopping curves had been attained in regular service, and the high efficiency of the proposed train service was characterized as impracticable and chimerical by those opposed to the granting of the charter.

It is a notable fact that, while the effort to attain high acceleration in bringing electric trains to the required speed had involved costly extension of the application of motors to a number of cars throughout the train — being applied, in some cases, to the trucks of all the cars — practically no effort had previously been made to realize a higher rate of retardation, in regular service, than that which had been regularly employed in steam-railroad service, through the service application of the ordinary automatic air brake. Without attempting any discussion of the merits of multiple-control systems of electric locomotion, or the commercial limitation of the expense justified in extending the application of motors to a number of cars throughout the train, it may properly be suggested that commercial economy may not result from an indefinite extension of such systems. The inadequacy of a single motor car for the acceleration of a train of several cars easily justifies the application of motors to the trucks of one or more additional cars, depending upon the number of cars in the train; but it may also be readily understood that a point may be reached, in the increased acceleration due to multiplication of motors, beyond which the addition of other motors is accompanied by too small a measure of increased acceleration to justify the added expense of installation and maintenance.

An illustration may be found in the operation of city waterworks' systems. It is a well-understood fact that refinement of pumping machinery is justified up to the attainment of a practical duty of somewhere in the neighborhood of 90,000,000 gallons; beyond this, further refinement, whereby an increased duty is accomplished, is attended by an increased cost of plant and of repairs and necessitates a higher grade of skilled oversight and attendance which more than compensates for the fuel economy acquired. It

is not fuel economy, but it is commercial economy of operation, which defines the limit of such refinement and establishes a duty which may not be exceeded with commercial advantage. Similarly, the extension of multiple-control systems to the application of motors to more than a certain limited proportion of the axles upon a train may easily be attained by an ultimate cost whereby economy of operation is impaired.

The pertinence of the foregoing observation lies merely in the fact that, while the application of multiple-control systems has, in some cases, apparently been pushed to extremes, in an effort to improve electrical train service, by attaining the very highest acceleration at the sacrifice of commercial economy, the absence of any effort to attain a fuller measure of the possible rate of retardation, in stopping, is the more noteworthy. That materially increased stopping efficiency may with propriety be employed in high-speed train service, it is the purpose of this paper to demonstrate; and, as every start, requiring high acceleration, is necessarily attended by a corresponding stop, in which a higher rate of retardation correspondingly improves the character of the train service, it is obvious that, if increased expense is justified in moderately increasing the rate of acceleration, materially increased stopping efficiency, at a comparatively small cost, is entitled to careful consideration.

To those who are familiar with the results of experiments with the friction of brake-shoes upon car-wheels and the difference in the conditions of brake application at high speed from those at low speed, the proposal to increase the force of application of the brake-shoes upon the wheels at high speeds will excite no comment.

The various trustworthy experiments upon brake-shoe friction have uniformly demonstrated a declining ratio of the friction to the pressure of the shoe upon the wheel at increased speeds. For the same brake-shoe pressure the friction excited at a speed of 60 miles an hour is but about one-half that which occurs when the speed is but 20 miles an hour. Other causes result in a reduction of the brake-shoe friction during continued application of the brakes; and this result combines with the increase of the friction through reduction of speed, during the retardation of the train, to maintain a comparatively uniform, though slightly increasing, rate of friction throughout the stop, until quite near its close. Thus, the average rate of retardation of the brakes, when applied to the wheels at a speed of 60 miles an hour, is about one-half of that acquired

with the same brake-shoe pressure when the initial speed is but 20 miles an hour. It is evident, therefore, that the same rate of retardation — which may with entire propriety be employed at all speeds — can only be acquired by increased pressure of the brake-shoes upon the wheels, to correspond with the reduced rate of friction occurring at the higher speeds.

Moreover, an application of the brakes which will produce a given rate of retardation at one speed, without danger to the rolling-stock or discomfort to the passengers, may also be applied at any other speed with no more danger or discomfort. The high-speed brake was designed more particularly for use upon high-speed trains, and it employs a considerably greater brake-shoe pressure in emergency applications than that of the ordinary quick-action brake, to more nearly realize the rate of retardation obtained in the emergency application of the quick-action brake upon trains of lower speeds. At such a high speed as 60 miles an hour, however, even the emergency application does not develop greater brake-shoe friction than does a full service application of the quick-action brake at a speed of 20 miles an hour. It is true that the service application is attended by a comparatively gradual application of the brake-shoe pressure, while the emergency application develops the greater brake-shoe pressure very quickly; but experience and observation seemed fully to justify the conclusion that the reduced rate of friction at the higher speeds would permit the use of even the high-speed brake without noticeable shock or disagreeable sensation.

Though the conviction thus expressed three and one-half years ago was based upon observation, experience and knowledge of the results of experiments upon brake-shoe friction, it was, nevertheless, so far as practical employment in train service was concerned, a theoretical conclusion. Since that time experiments in the use of the high-speed brake upon passenger trains have amply confirmed the writer's views upon this subject and demonstrated the absence of disagreeable effect as well as the highly increased rate of retardation in employing the emergency application of the high-speed brake for stops in high-speed train service. The time and distance saved in such stops permit the employment of the maximum speed up to a comparatively short distance from the stopping point and cause the train to be brought to a quick, smooth stop in much less than half the time and distance required for an ordinary service stop.

That the shortened running time and increased efficiency of high-speed train service — particularly local express-train service — by the employment of such higher rate of retardation, may be attained at a small fraction of the expense at which a lesser improvement in such efficiency can be obtained through the increased acceleration resulting from extending the multiple-control system from the use of motors upon one-half the cars in the train to their application to all of them, seems hardly open to doubt. The neglect to take advantage of this higher rate of retardation would seem to be attributable chiefly to the long-established doctrine that emergency applications must not be employed for service stops, under far different conditions. It is to be understood that such a doctrine still applies, with all its force, to the operation of passenger trains at moderate speed, as well as to freight-train service. It is only under the special conditions of uniform operation at high speeds — not less than 50 miles an hour — that the recommendation of a most powerful application of a most powerful brake, in all stops, properly applies.

In addition to the advantage of effecting a reduction of from 50 to 75 per cent in the time and distance required by a service application of the brakes, a collateral advantage of material importance is the much greater accuracy of the stop. In a stop by a service application of the brakes, the application is affected by the personal judgment of the operator, whereby an element of uncertainty is introduced which almost invariably requires a subsequent release and a second application of the brakes, in order to bring the train to a stop within the range of the station platform. This frequently involves more or less "drifting" of the train, at greatly reduced speed, to avoid stopping short of the station and not infrequently involves backing of the train because of inaccurate judgment in the application of the brakes, whereby the train runs beyond the stopping point. In the use of the emergency application, not only is the individual application of every brake very much more prompt and powerful, but the rate of serial application from car to car is almost instantaneous and is automatically established to the exclusion of any influence of the operator's judgment. Grade and alignment of the roadway, of course, influence the stopping distance; but such influences are readily determined for each stopping point, and the point at which the motive power should be shut off and the emergency application of the brakes should occur, may be

designated by a post or other permanent signal, whereby the train will be brought to a stop at the desired stopping point.

In comparison with the rate of acceleration, in starting steam-railroad trains, the rate of retardation in ordinary service stops has been so high that it is not unnatural that increased efficiency of train service has suggested higher rates of acceleration in starting, rather than improved retardation in stopping; but it should now be clear that a really efficient high-speed train service may be obtained only by also employing the maximum practical rate of retardation, by which so large a reduction of the time and distance of stopping is counted. Electric train service furnishes exceptional conditions for attaining the maximum retardation, as well as the maximum rate of acceleration — though for different reasons. Where trains are drawn by steam locomotives the conditions existing at the locomotive and the variable load carried in the tender involve limiting the braking power so that the retarding force is considerably inferior to that realized upon the cars. Where electricity is employed the motive power is applied directly to the cars themselves in such a manner that the maximum braking efficiency may be obtained as well upon motor as upon other cars, and the whole train is thus subject to the maximum rate of retardation.

While the special conditions of high-speed train service permit realization of the maximum obtainable retardation in ordinary station stops, it will be understood, of course, that all the ordinary means of general brake efficiency are contemplated in connection with the brake apparatus. In a paper presented to the American Institute of Electrical Engineers, and published in the January, 1903, volume of proceedings, the writer pointed out the more important features of the brake apparatus for attaining such high efficiency. They included efficient foundation brake-gear automatic slack adjuster, to maintain the minimum piston stroke in the brake cylinders, and brake beams hung between the wheels and adapted to regulate the brake-shoe pressure so as to compensate for the transfer of weight from the rear to the forward pair of wheels of each truck during the application of the brakes.

In addition to such general considerations an exceedingly important element of braking efficiency is the character of the brake-shoes applied to the wheels. Extensive experiments have demonstrated a very wide variation in the frictional quality of brake-shoes of different materials, and, further, a marked difference in the friction of the same brake-shoe upon wheels of different materials.

It is, in general, found that the maximum frictional resistance occurs in the application of soft cast-iron shoes to chilled cast-iron wheels, and the friction-producing quality generally declines as harder brake-shoe materials are employed. It should not be concluded, however, from this general relation of the hardness of the brake-shoe materials to the frictional quality, that soft material only should be employed in brake-shoes. Beside the cost of soft brake-shoes, which wear rapidly, the trouble and expense of replacement, together with the complications arising from rapid wear, are highly persuasive elements in favor of the use of harder materials. If the inferior frictional quality of the harder brake-shoes is compensated by correspondingly increased pressure of the brake-shoes upon the wheels, the operative objection to the hard brake-shoe practically disappears. The question is, to a large extent, a commercial one. Increased pressure upon the harder shoes involves, of course, somewhat increased wear; but when, in each case, the brake-shoe pressure is so adapted to its frictional quality that the maximum retarding friction is acquired, the practical question resolves itself into the relative cost of initial installation and of subsequent maintenance—to which must be added due consideration of trouble and annoyance arising from the necessity of frequent attention.

Within the past two or three years, two different series of experiments with the high-speed brake have furnished most interesting and important information bearing upon this subject. In one series, soft cast-iron brake-shoes were employed with chilled cast-iron wheels. In the other the "Diamond S" form of brake-shoe (of hard cast-iron, with steel inserts) was used with steel-tired wheels. Otherwise, the conditions were fairly comparable, the tests being conducted in the same general locality. In the case where soft cast-iron shoes were employed, the initial air-pressure in the brake-cylinder was about 85½ lbs., which became reduced, toward the end of the stop, to 60 lbs. In the tests with the Diamond S brake-shoe, the initial air-pressure on the brake-cylinder was also about 85½ lbs., which, by the use of special high-speed reducing valves, became reduced to a final minimum of from about 69 lbs., from a speed of 80 miles an hour, to about 78 lbs., in stopping a six-car train from a speed of 50 miles an hour. Moreover, in some instances, a brake-cylinder pressure of 75 lbs. or more occurred in applications of the brakes at speeds of 20 miles per hour (and even less), without producing wheel-sliding of an injurious character or exceeding that which occurred with

the use of the soft cast-iron brake-shoe, when the final minimum air-pressure in the brake-cylinder was but 60 lbs. The stopping distances were phenomenally short in the tests with the Diamond S brake-shoe, averaging 602 ft. from a speed of 50 miles an hour, 982 ft. at 60 miles an hour, and 1334 ft. at 70 miles an hour — the shortest authentic stops on record.

It is true that these tests were made in dry weather, and that the rails were more or less affected by sand, in which the soil of the country abounded, and particles of which were carried about by wind. It is very doubtful whether such high terminal brake-cylinder pressure might be safely employed even with such hard brake-shoes, under the varying rail conditions of regular service — the corresponding total brake-shoe pressures, as customarily calculated, being from 104 to 117 per cent of the weight of the braked cars; but these experiments clearly illustrate both the fact that wide difference in the frictional qualities of brake-shoes should be given proper consideration in determining the brake-shoe pressure, and also the fact that, with a properly determined pressure, certain forms of hard brake-shoes may yield as good, or perhaps even better, average retarding influence than soft cast-iron brake-shoes. It is worthy of note that the material in the brake-shoes employed in these experiments was so hard that a number of the shoes were broken during the tests — but without apparently affecting their utility, inasmuch as the form of the shoes remained unchanged, the parts being held in place by a steel plate cast in the outer surface of the shoe.

The foregoing considerations assume the use of the automatic air brake. Inasmuch as high-speed *trains* have been under consideration, no other form than an automatic brake could properly be considered. In the case of a service employing single cars, the advantage of an automatic brake practically disappears and more simple forms of apparatus may be employed to advantage; but, where two or more cars are assembled in trains, and particularly in high-speed trains, the necessity of providing for the contingency of train partings permits but the one prudent and safe course of employing an automatic brake, and, thus far, the automatic air brake alone has become safely established as meeting all the requirements of service. The necessity of the most efficient high-speed train service requires, in addition, the most forcible application of the most efficient form of automatic air brake — the emergency application of the "high-speed" brake.

ALTERNATING-CURRENT MOTORS.

BY CHARLES PROTEUS STEINMETZ.

I.

In recent years a number of types of alternating-current motors have become of interest, which, while not new in their general principles, but antedating even the polyphase induction motor, have been for some time overshadowed by the latter, due to its greater simplicity, resulting from the absence of the commutator, and its constancy of speed.

With the rapid extension of the applications of electricity, alternating-current motors were demanded for railway and similar classes of work, which give high-starting torque efficiency and high efficiency over a wide range of speed; that is a speed-torque characteristic similar to that of the direct-current series motor. The characteristic of the alternating-current induction motor, however, is that of a constant-speed motor, and indeed the polyphase induction motor can theoretically be considered as an adaptation of the direct-current shunt motor to alternating current, as I have shown elsewhere. By the introduction of the commutator almost any speed-torque characteristic can be produced. A number of types of such commutator motors have been produced and more or less developed, but thus far practical experience has not yet advanced so far as to weed out the less desirable types. To enable a critical judgment of their relative advantages and disadvantages, I shall endeavor in the following to give a general theory of the alternating-current motor, applicable alike to the induction and commutator motors.

The starting point of the theory of the polyphase and single-phase induction motor usually is the general alternating-current transformer, and from the equations of the general alternating-current transformer the induction motor equations can be developed.[1] Coming, however, to the commutator motors, this method becomes less suitable.

1. *Transactions* A. I. E. E., 1895.

In its general form the alternating-current motor consists of one or more stationary electric circuits magnetically related to one or more rotating electric circuits. These circuits can be excited by alternating currents, or some by alternating, others by direct current, or closed upon themselves, etc., and connection can be made to the rotating member either by collector rings — that is, to fixed points of the windings — or by commutator — that is to fixed points in space.

The alternating-current motors can be subdivided into two classes — those in which the electric and magnetic relations between stationary and moving members do not vary with their relative positions, and those in which they vary with the relative positions of stator and rotor. In the latter a cycle of rotation exists, and therefrom the tendency of the motor results to lock at a speed giving a definite ratio between the frequency of rotation and the frequency of impressed e.m.f. Such motors, therefore, are synchronous motors.

The main types of synchronous motors are as follows:

(1) One member supplied with alternating and the other with direct current — polyphase or single-phase synchronous motors.

(2) One member excited by alternating current, the other containing a single circuit closed upon itself — synchronous induction motors.

(3) One member excited by alternating current, the other of different magnetic reluctance in different directions (as polar construction) — reaction motors.

(4) One member excited by alternating current, the other by alternating current of different frequency or different direction of rotation — general alternating-current transformer or frequency converter.

No. 1 is the synchronous motor of the electrical industry. Nos. 2 and 3 are used occasionally to produce synchronous rotation without direct-current excitation, and of very great steadiness of the rate of rotation, where weight — efficiency and power factor are of secondary importance. No. 4 is used to some extent as frequency converter.

In the following I shall discuss only that type of motor in which the electric and magnetic relations between the stator and rotor do not vary with their relative positions, and the torque is, there-

fore, not limited to a definite synchronous speed. This requires that the rotor when connected to the outside circuit is connected through a commutator, and when closed upon itself several closed circuits exist, displaced in position from each other so as to offer a resultant closed circuit in any direction. In the theoretical investigation I shall use the method of complex quantities, the application of which to alternating-current phenomena I outlined in a paper before a previous congress.[2] The extension of this method to vector products as torque and power is given in the appendix.[3]

II.

An alternating current I flowing through an electric circuit produces a magnetic flux Φ interlinked with this circuit. Considering equivalent sine waves of I and Φ, Φ lags behind I by the angle of hysteretic lag a. This magnetic flux Φ induces an e.m.f. $E = 2\pi N n \Phi$, where $N =$ frequency, $n =$ number of turns of electric circuit. This induced e.m.f. E lags 90 deg. behind the magnetic flux Φ, hence consumes an e.m.f. 90 deg. ahead of Φ, or $90 - a$ deg. ahead of I. This may be resolved in a wattless component: $E = 2\pi N n \,\Phi \cos a = 2\pi N\, L\, I = x\, I$, the e.m.f. consumed by self-induction, and an energy component: $E'' = 2\pi N n\, \Phi \sin a = 2\pi N\, H\, I = r''\, I =$ e.m.f. consumed by hysteresis (eddy currents, etc.), and is, therefore, in vector representation denoted by

$E' = -j\, x\, I$ and $E'' = r''\, I$

where $x = 2\pi N\, L =$ reactance, $L =$ inductance,

$r'' =$ effective hysteretic resistance.

The ohmic resistance of the circuit, r', consumes an e.m.f. $r' I$ in phase with the current, and the total or effective resistance of the circuit is, therefore, $r = r' + r''$, and the total e.m.f. consumed by the circuit, or the impressed e.m.f. is

$$E = (r - j\, x)\, I = Z\, I$$

where

$Z = r - jx =$ impedance, in vector notation,

$z = \sqrt{r^2 + x^2} =$ impedance, in absolute terms.

If an electric circuit is in inductive relation to another electric circuit, it is advisable to separate the inductance L of the circuit into two parts—the self-inductance S, which refers to that part of

2. Chicago, 1903, *Proceedings* Int. Elec. Cong., 1894.
3. See also *Transactions* A. I. E. E., 1899.

the magnetic flux produced by the current in one circuit which is interlinked only with this circuit but not with the other circuit, and the mutual inductance, M, which refers to that part of the magnetic flux interlinked also with the second circuit. The desirability of this separation results from the different character of the two components: The self-inductance induces a wattless e.m.f. and thereby causes a lag of the current, while the mutual inductance transfers power into the second circuit, hence generally does the useful work of the apparatus. This leads to the distinction between the self-inductive impedance $Z_0 = r_0 - j x_0$ and the mutual inductive impedance $Z = r - j x$.

r_0 is the coefficient of power consumption by ohmic resistance, hysteresis and eddy currents of the self-inductive flux — effective resistance.

x_0 is the coefficient of e.m.f. consumed by the self-inductive flux — self-inductive reactance.

r is the coefficient of power consumption by hysteresis and eddy currents due to the mutual magnetic flux (hence contains no ohmic resistance component).

x is the coefficient of e.m.f. consumed by the mutual magnetic flux.

The e.m.f. consumed by the circuit is then

$$E = Z_0 I + Z I$$

If one of the circuits rotates relatively to the other, then in addition to the e.m.f. of self-inductive impedance: $Z_0 I$ and the e.m.f. of mutual-inductive impedance or e.m.f. of alternation: $Z I$, an e.m.f. is consumed by rotation. This e.m.f. is in phase with the flux through which the coil rotates — that is the flux parallel to the plane of the coil — and proportional to the speed — that is the frequency of rotation — while the e.m.f. of alternation is 90 deg. ahead of the flux alternating through the coil — that is the flux parallel to the axis of the coil — and proportional to the frequency. If, therefore, Z' is the impedance corresponding to the former flux, the e.m.f. of rotation is $j a Z' I$, where a is the ratio of frequency of rotation to frequency of alternation, or the speed expressed as a fraction of synchronous speed. The total e.m.f. consumed in the circuit is thus: $E = Z_0 I + Z I + j a Z' I$.

Applying now these considerations to the alternating-current motor, we assume all circuits reduced to the same number of turns — that is, selecting one circuit, of n effective turns, as starting

point, if n_1 = number of effective turns of any other circuit, all the e.m.f's. of the latter circuit are divided, the currents multiplied with the ratio n_1/n, the impedances divided, the admittances multiplied with $(n_1/n)^2$ This reduction of the constants of all circuits to the same number of effective turns is convenient by eliminating constant factors from the equations, and so permitting a direct comparison. When speaking, therefore, in the following of the impedance, etc., of the different circuits, we always refer to their reduced values (as it is customary in induction motor designing practice).

Let then, in Fig. 1, E_0, I_0, Z_0 = impressed e.m.f., current and self-inductive impedance resp. of a stationary circuit, E_1, I_1, Z_1=

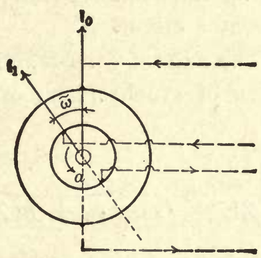


FIG. 1.

impressed e.m.f., current and inductive impedance respectively of a rotating circuit, ω = angle between the axis of the two circuits, Z = mutual-inductive or "exciting" impedance in the direction of the axis of the stationary coil, Z' = exciting impedance in the direction of the axis of the rotating coil, Z'' = exciting impedance at right angles to the latter axis, and a = speed, as fraction of synchronism. It is then:

In the stationary coil:

E.m.f. consumed by self-inductive impedance: $Z_0\, I_0$

E.m.f. consumed by mutual-inductive impedance: $Z\ (I_0 + I_1 \cos\omega)$ since the m.m.f. acting in the direction of the axis of the stationary coil is the resultant of both currents. Hence:

$$E_0 = Z_0\, I_0 + Z\ (I_0 + I_1 \cos\omega)$$

In the rotating circuit, it is:

E.m.f. consumed by self-inductive impedance: $Z_1\, I_1$

E.m.f. consumed by mutual-inductive impedance or "e.m.f. of alteration:" $Z'\ (I_1 + I_0 \cos\omega)$

E.m.f. of rotation: $j a Z'' I_0 \sin \omega$

Hence the impressed e.m.f.:

$$E_1 = Z_1 I_1 + Z' (I_1 + I_0 \cos \omega) + j a Z'' I_0 \sin \omega$$

In a structure with uniformly distributed winding, as used in induction motors, repulsion motors, etc., $Z' = Z'' = Z$, that is, the exciting impedance is the same in all directions.

Z is the reciprocal of the "exciting admittance," Y of the induction motor theory.

In the most general case, of a motor containing n circuits, of which some are revolving, some stationary, if:

E_k, I_k, Z_k = impressed e.m.f., current and self-inductive impedance respectively of any circuit k

Z^1, and Z^{11} = exciting impedance parallel and at right angles respectively to the axis of a circuit i,

ω_k^i = angle between the axes of coils k and i, and

a = speed, as fraction of synchronism, or "frequency of rotation."

It is then, in a coil i:

$$E_i = Z_i I_i + Z^1 \sum_1^n{}_k I_k \cos \omega_k^i + ja Z^{11} \sum_1^n{}_k I_k \sin \omega_k^i$$

where:

$Z_i I_i$ = e.m.f. of self-inductive impedance.

$Z^1 \sum_1^n{}_k I_k \cos \omega_k^i$ = e.m.f. of alternation

$E_i' = jaZ^{11} \sum_1^n{}_k I_k \sin \omega_k^i$ = e.m.f. of rotation

which latter $= o$ in a stationary coil, in which $a = o$.

The power output of the motor is the sum of the powers of all the e.m.fs. of rotation, hence, in vector denotation[4]:

$$P = \sum_1^n{}_i \,/\, E_i' I_i \,/^1$$

$$= a \sum_1^n{}_i \,/\, j Z^{11} \sum_1^n{}_k I_k \sin \omega_k^i ,\ I_i \,/^1$$

and, therefore, the torque, in synchronous watts[5]:

$$T = \frac{P}{a} = \sum_1^n{}_i \,/\, j Z^{11} \sum_1^n{}_k I_k \sin \omega_k^i,\ I_i \,/^1$$

4. See appendix. Also *Transactions* A. I. E. E., 1899.
5. See *Transactions* A. I. E. E., 1897, 1898, 1900.

The power input, in vector denotation, is:

$$P_0 = \sum_1^n E_i, I_i /$$
$$= \sum_1^n / E_i, I_i /^1 + \sum_1^n / E_i, I_i /^j$$
$$= P_0^1 + j P_0^j$$

and therefore:

P_0^1 = true power input

P_0^j = wattless voltampere input

$Q_0 = \sqrt{(P_0^1)^2 + (P_0^j)^2}$ = apparent or voltampere input

$\frac{P}{P_0^1}$ = efficiency; $\frac{T}{P_0^1}$ torque efficiency;

$\frac{P}{Q_0}$ = apparent efficiency; $\frac{T}{Q_0}$ = apparent torque efficiency

$\frac{P_0^1}{Q_0}$ = power factor

From the n circuits: $i = 1, 2, \ldots$ thus result n linear equations, with $2n$ complex variables: I_i and E_i.

Hence n further conditions must be given to determine the variables. These obviously are the conditions of operation of the n circuits.

Impressed e.m.f's. E_i may be given.

Or circuits closed upon themselves: $E_i = o$.

Or circuits connected in parallel: $c_i E_i = c_k E_k$, where c_i and c_k are the reduction factors of the circuits to equal number of effective turns, as discussed before.

Or circuits connected in series: $c_i I_i = c_k I_k$, etc.

When a rotating circuit is connected through a commutator, the frequency of the current in this circuit obviously is the same as the impressed frequency. Where, however, a rotating circuit is permanently closed upon itself, its frequency may differ from the impressed frequency, as, for instance, in the polyphase induction motor it is the frequency of slip $s = 1 - a$, and the self-inductive reactance of the circuit, therefore, is: $s\,x$, though in its reaction upon the stationary system the rotating system necessarily is always of full frequency.

After this introduction we come now to the discussion of a few motor types. We shall, however, consider only such types as have been more or less developed commercially or at least seriously considered.

III.

(1) *Polyphase Induction Motor.*

In the polyphase induction motor a number of primary circuits, displaced in position from each other, are excited by polyphase e.m.f's. displaced in phase from each other by a phase angle equal to the position angle of the coils. A number of secondary circuits are closed upon themselves. The primary usually is the stator, the secondary the rotor.

In this case the secondary system always offers a resultant closed circuit in the direction of the axis of each primary coil, irrespective of its position.

Let us assume two primary circuits in quadrature as simplest form, and the secondary system reduced to the same number of phases and the same number of turns per phase as the primary system. With three or more primary phases the method of procedure and the resultant equations are essentially the same.

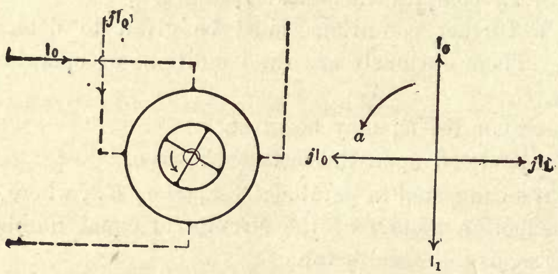


FIG. 2.— POLYPHASE INDUCTION MOTOR.

Let in the motor shown diagrammatically in Fig. 2:

E_0 and jE_0, I_0 and jI_0, Z_0 = impressed e.m.f's., currents and self-inductive impedance respectively of the primary system.

o, I_1 and jI_1, Z_1 = impressed e.m.f., currents and self-inductive impedance respectively of secondary system, reduced to primary.

Z = mutual-inductive impedance between primary and secondary.

a = speed; $s = 1 - a$ = slip, as fraction of synchronism.

The equation of the primary circuit is then:

$$E_0 = Z_0 I_0 + Z \ (I_0 - I_1) \qquad (1)$$

The equation of the secondary circuit:

$$o = Z_1 I_1 + Z\ (I_1 - I_0) + jaZ\ (jI_1 - jI_0) \tag{2}$$

from (2) follows:

$$I_1 = I_0 \frac{Z_0\,(1-a)}{Z\,(1-a) + Z_1} = I_0 \frac{Zs}{Zs + Z_1} \tag{3}$$

and, substituted in (1):

Primary current:

$$I_0 = E_0 \frac{Zs + Z_1}{ZZ_0 s + ZZ_1 + Z_0 Z_1} \tag{4}$$

Secondary current:

$$I_1 = E_0 \frac{Zs}{ZZ_0 s + ZZ_1 + Z_0 Z_1}, \tag{5}$$

Exciting current:

$$I_{00} = I_0 - I_1 = E_0 \frac{Z_1}{ZZ_0 s + ZZ_1 + Z_0 Z_1} \tag{6}$$

E.m.f. of rotation:

$$E^1 = jaZ\ (jI_1 - jI_0) = aZ\ (I_0 - I_1)$$

$$= aE_0 \frac{ZZ_1}{ZZ_0 s + ZZ_1 + Z_0 Z_1}$$

$$= (1-s)\ E_0 \frac{ZZ_1}{ZZ_0 s + ZZ_1 + Z_0 Z_1} \tag{7}$$

It is, at synchronism: $s = o$:

$$I_0 = \frac{E_0}{Z + Z_0};\quad I_1 = o\,;\ I_{00} = I_0\,;\ E^1 = \frac{E_0 Z}{Z + Z_0} = \frac{E_0}{1 + Z_0/Z}$$

At standstill: $s = 1$:

$$I_0 = \frac{E_0 (Z + Z_1)}{ZZ_0 + ZZ_1 + Z_0 Z_1};\quad I_1 = \frac{E_0 Z}{ZZ_0 + ZZ_1 + Z_0 Z_1};$$

$$I_{00} = \frac{E_0 Z_1}{ZZ_0 + ZZ_1 + Z_0 Z_1};\quad E^1 = o$$

Introducing as parameter the counter e.m.f., or e.m.f. of mutual induction:

$$E = E_0 - Z_0 I_0$$

or:

$$E_0 = E + Z_0 I_0$$

it is, substituted:

Counter e.m.f.:

$$E = E_0 \frac{ZZ_1}{ZZ_0 s + ZZ_1 + Z_0 Z_1} \tag{8}$$

hence:

Primary impressed e.m.f.:

$$E_0 = E \frac{ZZ_0 s + ZZ_1 + Z_0 Z_1}{ZZ_1} \tag{9}$$

E.m.f. of rotation:

$$E^1 = Ea = E\ (1 - s). \tag{10}$$

Secondary current:

$$I_1 = \frac{Es}{Z_1} \tag{11}$$

Primary current:

$$I_0 = E\frac{Zs + Z_1}{ZZ_1} = \frac{Es}{Z_1} + \frac{E}{Z} \tag{12}$$

Exciting current:

$$I_{00} = \frac{E}{Z} \tag{13}$$

These are the equations from which the transformer theory of the polyphase induction motor starts.

Since the frequency of the secondary induced currents is the frequency of slip, hence varies with the speed $a = 1 - s$. the secondary self-inductive reactance also varies with the speed, and so the impedance:

$$Z_1 = r_1 - jsx_1 \tag{14}$$

The power output of the motor, per circuit, is:

$$P = /E^1, I_1/$$

$$= \frac{e_0^{\ 2}\, z^2\, s\ (1 - s)}{[ZZ_0 s + ZZ_1 + Z_0 Z_1]^2}\ (r_1 + jsx_1) \tag{15}$$

where the brackets [] denote the absolute value of the term included by it, and the small letters e_0, z, etc., the absolute values of the vectors E_0, Z, etc.

Since the imaginary term of power seems to have no physical meaning, it is:

Mechanical power output:

$$P = \frac{e_0^{\ 2}\, z^2\, s\ (1 - s)\ r_1}{[ZZ_0 s + ZZ_1 + Z_0 Z_1]^2} \tag{16}$$

This is the power output at the armature conductors, hence includes friction and windage.

The torque of the motor is:

$$T = \frac{P}{1-s} = \frac{e_0^{\ 2}\ z^2\, r_1\, s}{[ZZ_0 s + ZZ_1 + Z_0 Z_1]^2} + j\frac{e_0^{\ 2}\ z^2\, x_1\, s}{[ZZ_0 s + ZZ_1 + Z_0 Z^1]^2} \tag{17}$$

The imaginary component of torque seems to represent the radial force or trust acting between stator and motor. Omitting it, it is:

$$T = \frac{e_0^{\ 2}\ z^2\, r_1\, s}{[ZZ_0 s + ZZ_1 + Z_0 Z^1]^2} \tag{18}$$

The power input of the motor per circuit is:

$$P_0 = /E_0, I_0/$$
$$= e_0^2/1, \frac{Zs + Z_1}{ZZ_0 s + ZZ_1 + Z_0 Z_1}/ \quad (19)$$
$$= P_0^1 + j P_0^j$$

where: P_0^1 = true power, P_0^j = reactive or "wattless power,"

$Q_0 = \sqrt{P_0^{1^2} + P_0^{j^2}}$ = apparent power, or voltampere input.

Herefrom follows power factor, efficiency, etc.

Introducing the parameter: E, or absolute: e, **it is:**

Power output:

$$P = /E^1, I_1/$$
$$= /ea, \frac{es}{Z_1}/$$
$$= e^2 sa/1, \frac{1}{Z_1}/$$
$$= \frac{e^2 sar_1}{z_1^2} + j\frac{e^2 s^2 ax_1}{z_1^2}$$
$$= \frac{i_1^2 ar_1}{s} + j\, i_1^2 ax_1 \quad (20)$$

Power input:

$$P_0 = /E_0, I_0/$$
$$= e^2 /\frac{ZZ_0 s + ZZ_1 + Z_0 Z_1}{ZZ_1}, \frac{Zs + Z_1}{ZZ_1}/$$
$$= e^2 /\frac{Z_0(Zs + Z_1)}{ZZ_1} + 1, \frac{Zs + Z_1}{ZZ_1}/$$
$$= e^2 \left[\frac{Zs + Z_1}{ZZ^1}\right]^2 \left\{ /Z_0 1/ + e^2/1, \frac{s}{Z_1} + \frac{1}{Z} \right\}$$
$$= e^2 \left[\frac{Zs + Z_1}{ZZ_1}\right]^2 \left\{ /Z_0, 1/ + \frac{e^2 s}{z_1^2}/Z_1, 1/ + \frac{e^2}{z^2}/Z, 1/ \right\}$$
$$= e^2 \left[\frac{Zs + Z_1}{ZZ_1}\right]^2 \left\{ (r_0 + jx_0) + \frac{e^2 s}{z_1^2}(r_1 + jsx_1) + \frac{e^2}{z^2}(r + j^1 x) \right\}$$
$$= i_0^2 (r_0 + jx_0) + i_1^2 \left(\frac{r_1}{s} + j\, x_1\right) + i_{00}^2 (r + jx)$$

And since: $\frac{r_1}{s} = \frac{a + s}{s} r_1 = \frac{ar_1}{s} + r_1$, and $\frac{i_1^2 ar_1}{s} = P$, it is:

$$P_0 = (i_0 r_0 + i_1^2 r_1 + i_{00}^2 r + P) + j(i_0^2 x_0 + i_1^2 x_1 + i_{00}^2 x) \quad (21)$$

Where:

$i_0^2\, r_0$ = primary resistance loss,

$i_1^2 r_1$ = secondary resistance loss,

$i_{00}^2 r$ = core loss (and eddy current loss),

P = output,

$i_0^2\, x_0$ = primary reactive voltamperes,

$i_1^2x^1$ = secondary reactive voltamperes,

$i_{00}^2 x$ = magnetizing voltamperes.

Introducing into the equations (3) (4) (5) (6) (8) the terms:

$$\left.\begin{aligned} Z_0 / Z &= \lambda_0 \\ Z_1 / Z &= \lambda_1 \end{aligned}\right\} \qquad (22)$$

Where λ_0 and λ_1 are small quantities, and: $\vartheta = \lambda_0 + \lambda_1$ is the "characteristic constant" of the induction motor theory, it is:

Primary current:

$$I_0 = \frac{E_0}{Z} \frac{s + \lambda_1}{s\lambda_0 + \lambda_1 + \lambda_0\lambda_1} = \frac{E_0}{Z} \frac{s + \lambda_1}{s\lambda_0 + \lambda_1} \qquad (23)$$

Secondary current:

$$I_1 = \frac{E_0}{Z} \frac{s}{s\lambda_0 + \lambda_1 + \lambda_0\lambda_1} = \frac{E_0}{Z} \frac{s}{s\lambda_0 + \lambda_1} \qquad (24)$$

Exciting current:

$$I_{00} = \frac{E_0}{Z} \frac{\lambda_1}{s\lambda_0 + \lambda_1 + \lambda_0\lambda_1} = \frac{E_0}{Z} \frac{\lambda_1}{s\lambda_0 + \lambda_1} \qquad (25)$$

E.m.f. of rotation:

$$E^1 = E_0\, a \frac{\lambda_1}{s\lambda_0 + \lambda_1 + \lambda_0\lambda_1} = E_0\, a \frac{\lambda_1}{s\lambda_0 + \lambda_1} \qquad (26)$$

Counter e.m.f.:

$$E = E_0 \frac{\lambda_1}{s\lambda_0 + \lambda_1 + \lambda_0\lambda_1} = E_0 \frac{\lambda_1}{s\lambda_0 + \lambda_1} \qquad (27)$$

As instance are shown, in Fig. 3, with the speed as abscissæ, the curves of a polyphase induction motor of the constants:

$e_0 = 320$ volts,

$Z = 1 - 10j$ ohms,

$Z_0 = Z_1 = .1 - .3j$ ohms

hence: $\lambda_0 = \lambda_1 = .0307 + .0069j$.

It is:

$$I_0 = \frac{320\{10.30s + (s + .1)j\}}{(1.03 + 1.63s) + j(.11 - 5.99s)} \text{ amps.}$$

$$T = \frac{2048\,(1-s)}{(1.03 + 1.63s)^2 + (.11 - 5.99s)^2} \text{ synchr. k.w.}$$

$$P = (1 - s)T$$

$$\tan \omega' = \frac{s + .1}{10.3s};\ \tan \omega'' = \frac{.11 - 5.99s}{1.03 + 1.63s}$$

$\cos(\omega' - \omega'')$ = power factor.

The curves show the well-known characteristics of the polyphase induction motor: approximate constancy of speed at all loads, and good efficiency and power factor within this narrow speed range, but poor constants at all other speeds.

(2) *Single-Phase Induction Motor.*

In the single-phase induction motor one primary circuit acts upon a system of closed secondary circuits which are displaced from each other in position on the secondary member.

Let the secondary be assumed as two-phase, that is containing or reduced to two circuits closed upon themselves at right angles to each other. While it then offers a resultant closed secondary circuit to the primary circuit in any position, the electrical disposition of the secondary is not symmetrical, but the directions parallel with the primary circuit and at right angles thereto are to

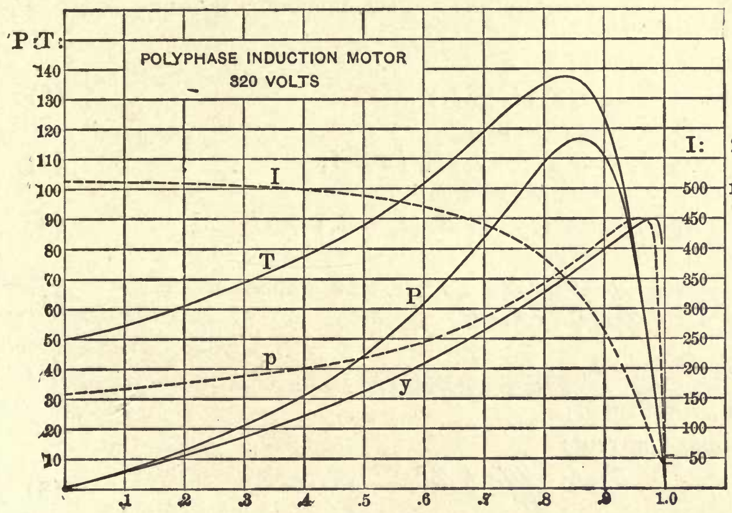


FIG. 3.

be distinguished. The former may be called the secondary energy circuit, the latter the secondary magnetizing circuit, since in the former direction power is transferred from the primary to the secondary circuit, while in the latter direction the secondary circuit can act magnetizing only.

Let, in the diagram Fig. 4:

E_0, I_0, Z_0 = impressed e.m.f., current and self-inductive impedance respectively of the primary circuit

I_1, Z_1 = current and self-inductive impedance respectively of the secondary energy circuit

I_2, Z_1 = current and self-inductive impedance respectively of the secondary magnetizing circuit

Z = mutual-inductive impedance

a = speed

and let: $s_0 = 1 - a^2$ (where s_0 is not the slip)

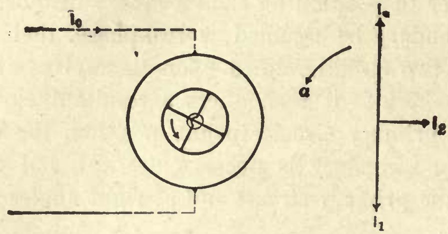


FIG. 4.— SINGLE-PHASE INDUCTION MOTOR.

It is then:

Primary circuit:

$$E_0 = Z_0 I_0 + Z (I_0 - I_1) \tag{1}$$

Secondary energy circuit:

$$o = Z_1 I_1 + Z (I_1 - I_0) + j a Z I_2 \tag{2}$$

Secondary magnetizing circuit:

$$o = Z_1 I_2 + Z I_2 + j a Z (I_0 - I_1) \tag{3}$$

hence:

$$I_1 = I_0 \frac{Z (Z s_0 + Z_1)}{Z^2 s_0 + 2 Z Z_1 + Z_1^2} \tag{4}$$

$$I_2 = - j a I_0 \frac{Z Z_1}{Z^2 s_0 + 2 Z Z_1 + Z_1^2} \tag{5}$$

and, substituted:

Primary current:

$$I_0 = E_0 \frac{Z^2 s_0 + 2 Z Z_1 + Z_1^2}{D} \tag{6}$$

Secondary energy current:

$$I_1 = E_0 \frac{Z (Z s_0 + Z_1)}{D} \tag{7}$$

Secondary magnetizing current:

$$I_2 = - j a E_0 \frac{Z Z_1}{D} \tag{8}$$

E.m.f. of rotation of secondary energy circuit:

$$E_1^1 = j a Z I_2 = a^2 E_0 \frac{Z^2 Z_1}{D} \tag{9}$$

E.mf. of rotation of secondary magnetizing circuit:

$$E_2^1 = j a Z (I_0 - I_1) = j a E_0 \frac{Z Z_1 (Z + Z_1)}{D} \tag{10}$$

where:

$$D = Z_0 (Z^2 s_0 + 2 Z Z_1 + Z_1^2) + Z Z_1 (Z + Z_1) \tag{11}$$

It is, at synchronism: $a = 1$, $s_0 = o$

$$I_0 = E_0 \frac{2Z + Z_1}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

$$I_1 = E_0 \frac{Z}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

$$I_2 = -j\,E_0 \frac{Z}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

$$E_1{}^1 = E_0 \frac{Z^2}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

$$E_2{}^1 = jE_0 \frac{Z(Z + Z_1)}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

Hence, at synchronism, the secondary current of the single-phase induction motor does not become zero, as in the polyphase motor, but both components of secondary current become equal.

At standstill: $a = o$, $s_0 = 1$ it is:

$$I_0 = E_0 \frac{Z + Z_1}{ZZ_0 + ZZ_1 + Z_0 Z_1}$$

$$I_1 = E_0 \frac{Z}{ZZ_0 + ZZ_1 + Z_0 Z_1}$$

$$I_2 = o; \; E_1{}^1 = o; \; E_2{}^1 = o$$

That is, primary and secondary current corresponding thereto have the same values as in the polyphase induction motor, page 8. This was to be expected.

Introducing as parameter the counter e.m.f. or e.m.f. of mutual induction:

$$E = E_0 - Z_0 I_0$$

and substituting for I_0 from (6), it is:

Primary impressed e.m.f.:

$$E_0 = E \frac{Z_0(Z^2 s_0 + 2ZZ_1 + Z_1^2) + ZZ_1(Z + Z_1)}{ZZ_1(Z + Z_1)} \tag{12}$$

Primary current:

$$I_0 = E \frac{Z^2 s_0 + 2ZZ_1 + Z_1^2}{ZZ_1(Z + Z_1)} \tag{13}$$

Secondary energy circuit:

$$I_1 = E \frac{Zs_0 + Z_1}{Z_1(Z + Z_1)} = \frac{s_0 E}{Z_1} + \frac{a^2 E}{Z + Z_1} \tag{14}$$

$$E_1{}^1 = a^2 E \frac{Z}{Z + Z_1} \tag{15}$$

Secondary magnetizing circuit:

$$I_2 = -j \frac{a E}{Z + Z_1} \tag{16}$$

$$E_2^1 = j\,a\,E \tag{17}$$

And:

$$I_0 - I_1 = \frac{E}{Z} \tag{18}$$

These equations differ from the equations of the polyphase induction motor by containing the term: $s_0 = (1 - a^2)$ instead of: $s = (1 - a)$, and by the appearance of the terms: $\frac{a\,E}{Z + Z_1}$ and: $\frac{a^2\,E}{Z + Z_1}$, of frequency $(1 + a)$, in the secondary circuit.

The power output of the motor is:

$$P = / E_1^1, I_1 /^1 + / E_2^1, I_2 /^1$$

$$= \frac{a^2\,e_0^2\,z^2}{[D]^2} \left\{ / Z Z_1, Z s_0 + Z_1 /^1 - / Z_1 (Z + Z_1), Z_1 /^1 \right\}$$

$$= \frac{a^2\,e_0^2\,z^2\,r_1\,(s_0\,z^2 - z_1^{\,2})}{[D]^2} \tag{19}$$

and the torque, in synchronous watts:

$$T = \frac{P}{a} = \frac{a\,e_0\,z^2\,r_1\,(s_0\,z^2 - z_1^{\,2})}{[D]} \tag{20}$$

From these equations it follows that at synchronism torque and power of the single-phase induction motor are already negative.

Torque and power become zero for:

$$s_0\,z^2 - z_1^{\,2} = o$$

hence:

$$a = \sqrt{1 - \left(\frac{z_1}{z}\right)^2} \tag{21}$$

that is, very slightly below synchronism: Let $z = 10$, $z_1 = .316$, it is: $a = .9995$.

In the single-phase induction motor, the torque contains the speed a as factor, and thus becomes zero at standstill.

Neglecting quantities of secondary order, it is, approximately:

$$I_0 = E_0 \frac{Z s_0 + 2 Z_1}{Z (Z_0 s_0 + Z_1) + 2 Z_0 Z_1} \tag{22}$$

$$I_1 = E_0 \frac{Z s_0 + Z_1}{Z (Z_0 s_0 + Z_1) + 2 Z_0 Z_1} \tag{23}$$

$$I_2 = - j a\,E_0 \frac{Z_1}{Z (Z_0 s_0 + Z_1) + 2 Z_0 Z_1} \tag{24}$$

$$E_1^1 = a^2\,E_0 \frac{Z Z_1}{Z (Z_0 s_0 + Z_1) + 2 Z_0 Z_1} \tag{25}$$

$$E_2^1 = j a\,E_0 \frac{Z Z_1}{Z (Z_0 s_0 + Z_1) + 2 Z_0 Z_1} \tag{26}$$

$$P + \frac{a^2 e_0^2 \; z^2 r_1 s_0}{[Z\,(Z_0 s_0 + Z_1) + 2\, Z_0 Z_1]^2} \qquad (27)$$

$$T = \frac{a\, e_0^2 \, z^2 r_1 s_0}{[Z\,(Z_0 s_0 + Z_1) + 2\, Z_0 Z_1]^2} \qquad (28)$$

This theory of the single-phase induction motor differs from that previously communicated (see note 1, ante), in that it represents more exactly the phenomena at intermediate speeds, which are only approximated in the transformer theory of the single-phase induction motor.

As instance are shown, in Fig. 5, with the speed as abscissæ, the curves of a single-phase induction motor, of the constants:

$$e_0 = 400 \text{ volts}$$
$$Z = 1 - 10j \text{ ohms}$$
$$Z_0 = Z_1 = .1 - .3j \text{ ohms}$$

hence:

$$I_0 = 400 \frac{N}{D} \text{ amps.}$$
$$N = (s + .2) - j(10s + .6 - .6a)$$
$$D = (.1 - .3j)N + (1 - 10j)\,(.1 - j\,(.3 - .3a))$$
$$T = \frac{1616\, a s}{[D]^2} \text{ synchr. kw.}$$

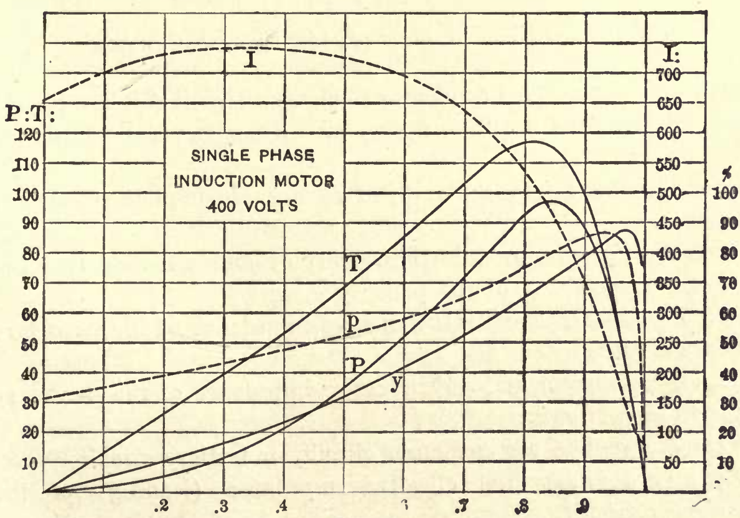


FIG. 5.

(3) *Single-phase Condenser Motor.*

The single-phase induction motor is not self-starting, as seen from the equations and diagram, Fig. 5. To secure

starting torque, either a commutator has to be used — that is, the motor started as repulsion motor or series motor, etc. — or a quadrature magnetic flux impressed upon the motor, that is the motor converted into a more or less unsymmetrical, polyphase motor. To a considerable extent used in practice are only the starting as repulsion motor, which will be discussed later, and the starting by a condenser in the tertiary circuit, both methods giving good starting efficiencies. The use of a condenser also permits to greatly increase the power factor in running, by retaining the condenser in circuit. This is usually carried out by employing a three-phase winding on the motor primary, of which two terminals are connected to the single-phase supply, two terminals permanently connected to a condenser, either directly or by step-

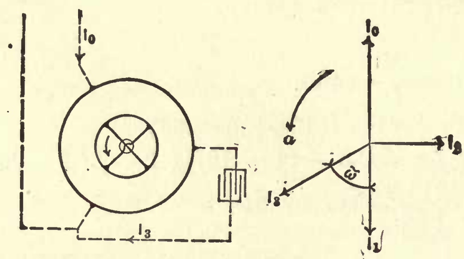


FIG. 6.— INDUCTION SINGLE-PHASE CONDENSER MOTOR.

up transformer. This condenser so closes a circuit displaced by 60 deg. in position from the primary circuit, as shown diagrammatically in Fig. 6.

Let, in the diagram Fig. 6, of such a single-phase condenser motor:

E_0, I_0, Z_0 = impressed e.m.f., current and self-inductive impedance respectively of the primary circuit,

I_1, Z_1 = current and self-inductive impedance of the secondary energy circuit,

I_2, Z_1 = current and self-inductive impedance of the secondary magnetizing circuit,

I_3 = current in the condenser circuit, or tertiary circuit,

$Z_3 = r_3 + j\, x_3$ = total effective impedance (leading) of the condenser circuit,

Z = mutual-inductive impedance,

ω = position angle between the axes of primary and tertiary circuit,

$a =$ speed.

The equations of the motor then are:

Primary circuit:

$$E_0 = Z_0 I_0 + Z (I_0 - I_1 - I_3 \cos \omega) \qquad (1)$$

Secondary energy circuit:

$$o = Z_1 I_1 + Z (I_1 - I_0 + I_3 \cos \omega) + j a Z (I_2 - I_3 \sin \omega) \qquad (2)$$

Secondary magnetizing circuit:

$$o = Z_1 I_2 + Z (I_2 - I_3 \sin \omega) + j a Z (I_1 - I_0 + I_3 \cos \omega) \qquad (3)$$

Tertiary or condenser circuit:

$$o = Z_3 I_3 + Z (I_3 - I_0 \cos \omega + I_1 \cos \omega - I_2 \sin \omega) \qquad (4)$$

These four linear equations give the four currents:

$$I_0, I_1, I_2, I_3$$

and thereby the e.m.f's. of rotation:

$$E^1_1 = j a Z (I_2 - I_3 \sin \omega) \qquad (5)$$

$$E_2 = j a Z (I_1 - I_0 + I_3 \cos \omega) \qquad (6)$$

and therefrom the torque, power output, input, etc.

Usually ω is made 60 deg. in this type of motor.

(4) *Polyphase Shunt Motor.*

Since the characteristics of the polyphase motor do not depend upon the number of phases, here, as in the preceding, a two-phase system may be assumed: that is, a two-phase stator winding acting upon a two-phase rotor winding, that is a closed coil rotor winding connected to the commutator in the same manner as in direct-current machines, but with two sets of brushes in quadrature position excited by a two-phase system of the same frequency. Mechanically the three-phase system here has the advantage to require three sets of brushes only instead of four with the two-phase system, but otherwise the general form of the equations and conclusions are not different.

Let E_0 and $j E_0 =$ e.m.f's. impressed upon the stator, E_1 and $j E_1 =$ e.m.f's. impressed upon the rotor, $\omega_0 =$ phase angle between e.m.f. E_0 and E_1 and $\omega_1 =$ position angle between the stator and rotor circuits. The e.m.f's. E_0 and $j E_0$ produce the same rotating m.m.f. as two e.m.f's. of equal intensity, but displaced in phase and in position by angle ω_0 from E_0 and $j E_0$, and instead of considering a displacement of phase ω_0 and a displacement of position ω_1 between stator and rotor circuits, we can, therefore, assume zero-phase displacement and displacement in position by angle $\omega_0 + \omega_1 = \omega$. Phase displacement between stator and rotor e.m.f's. is, therefore, equivalent to a shift of brushes.

Without losing in generality of the problem, we can, therefore, assume the stator e.m.f's. in phase with the rotor e.m.f's., and the polyphase shunt motor can thus be represented diagrammatically by Fig. 7.

Let, in the polyphase shunt motor, shown two-phase in diagram Fig. 7:

E_0 and jE_0, I_0 and jI_0, $Z_0 =$ impressed e.m.f's., currents and self-inductive impedance respectively of the stator circuits,

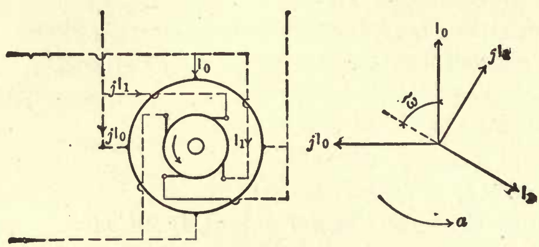


FIG. 7.—POLYPHASE SHUNT MOTOR.

cE_0 and jcE_0, I_1 and jI_1, $Z_1 =$ impressed e.m.f's., currents and self-inductive impedance resp. of the rotor circuits, reduced to the stator circuits by the ratio of effective turns c,

$Z =$ mutual-inductive impedance,

$a =$ speed, hence: $s = 1 - a =$ slip,

$\omega =$ position angle between stator and rotor circuits, or "brush angle."

It is then:

Stator:

$$E_0 = Z_0\, I_0 + Z\ (I_0 - I_1 \cos\omega + jI_1 \sin\omega) \qquad (1)$$

Rotor:

$$cE_0 = Z_1 I_1 + Z\ (I_1 - I_0 \cos\omega - jI_0 \sin\omega) + jaZ\ (jI_1 + I_0 \sin\omega - jI_0 \cos\omega) \qquad (2)$$

Substituting:

$$\left.\begin{array}{l} \sigma = \cos\omega + j \sin\omega \\ \delta = \cos\omega - j \sin\omega \end{array}\right\} \qquad (3)$$

it is

$\sigma\delta = 1$

and:

$$E_0 = Z_0 I_0 + Z\ (I_0 - \delta I_1) \qquad (4)$$

$$cE_0 = Z_1 I_1 + Z(I_1 - \sigma I_0) + jaZ(jI_1 - j\ I_0)$$
$$= Z_1 I_1 + sZ\ (I_1 - \sigma I_0) \qquad (5)$$

Herefrom follows:

$$I_0 = E_0 \frac{(s+\delta c)Z+Z_1}{sZZ_0+ZZ_1+Z_0Z_1} \tag{6}$$

$$I_1 = E_0 \frac{(\sigma s+c)Z+cZ_1}{sZZ_0+ZZ_1+Z_0Z_1} \tag{7}$$

for: $c=o$, this gives:

$$I_0 = E_0 \frac{sZ+Z_1}{sZZ_0+ZZ_1+Z_0Z_1}$$

$$I_1 = \sigma E_0 \frac{sZ}{sZZ_0+ZZ_1+Z_0Z_1}$$

that is, the polyphase induction motor equations of page 83 et seq.,

$\sigma = \cos\omega + j\sin\omega = 1^{\frac{\omega}{2\pi}}$ representing the displacement of position between stator and rotor currents.

This shows the polyphase induction motor as a special case of the polyphase shunt motor, for: $c=o$.

The e.m.f's. of rotation are:

$$E_1^1 = jaZ\ (jI_1 + I_0\sin\omega - jI_0\cos\omega)$$
$$= aZ\ (\sigma I_0 - I_1)$$

hence:

$$E_1^1 = aE_0 \frac{Z(\sigma Z_1 - cZ_0)}{sZZ_0+ZZ_1+Z_0Z_1} \tag{8}$$

The power output of the motor is:

$$P = /E_1^1, I_1/^1$$
$$= \frac{ae_0^2}{[sZZ_0+ZZ_1+Z_0Z_1]^2} /(\sigma Z_1 - cZ_0)Z, (\sigma s+c)Z+cZ_0/^1$$

which, suppressing terms of secondary order, gives:

$$P = \frac{ae_0^2\ z^2\ \{s(r_1+c(x_0\sin\omega - r_0\cos\omega))+c(r_1\cos\omega + x_1\sin\omega - cr_0)\}}{[sZZ_0+ZZ_1+Z_0Z_1]^2} \tag{9}$$

for: $c=o$, this gives:

$$P = \frac{a\ e_0^2\ z^2\ sr_1}{[sZZ_0+ZZ_1+Z_0Z_1]^2}$$

the same value as for the polyphase induction motor.

The power output becomes zero: $P=o$, for the slip:

$$s_0 = -c\frac{r_1\cos\omega + x_1\sin\omega - cr_0}{r_1 + c(x_0\sin\omega - r_0\cos\omega)} \tag{10}$$

This slip $s_0 = o$, or the motor output becomes zero at synchronism, if:

$$r_1\cos\omega + x_1\sin\omega - cr_0 = o$$

hence:

$$c = \frac{r_1\cos\omega + x_1\sin\omega}{r_0} \tag{11}$$

or, substituting:

$$\frac{x_1}{r_1} = \tan a_1 , \tag{12}$$

where a_1 is the phase angle of the rotor impedance, it is:

$$c = \frac{z_1}{r_0} \cos (a_1 - \omega) \tag{13}$$

or:

$$\cos (a_1 - \omega) = \frac{r_0}{z_1} c. \tag{14}$$

That is:

At given brush angle ω, a value of secondary impressed e.m.f; cE_0, exists, which makes the motor tend to synchronize at no load, and:

At given rotor impressed e.m.f.; cE_0, a brush angle ω exists, which makes the motor synchronize at no load.

Since r_0 is usually very much smaller than z_1, if c is not very large, it is:

$$\cos (a - \omega) = o,$$

hence:

$$\omega = 90° - a_1 \tag{15}$$

That is, if the brush angle ω is complimentary to the phase angle of the self-inductive rotor impedance a_1 the motor tends toward approximate synchronism at no load.

The rotor current:

$$I_1 = E_0 \frac{\sigma s Z + c (Z + Z_0)}{s Z Z_0 + Z Z_1 + Z_0 Z_1}$$

becomes zero, if:

$$c = - \sigma s \frac{Z}{Z + Z_0}$$

or, since Z_0 is small compared with Z, approximately:

$$c = - \sigma s = - s (\cos \omega + j \sin \omega)$$

hence, resolved:

$$c = - s \cos \omega$$

$$o = s \sin \omega$$

hence:

$$\left. \begin{aligned} \omega &= \sigma \\ c &= - s \end{aligned} \right\} \tag{16}$$

That is, the rotor current can become zero only if the brushes are set in line with the stator circuit or without shift, and in this case the rotor current, and therewith the output of the motor, becomes zero at the slip $s = - c$.

Hence such a motor gives a characteristic curve very similar to that of the polyphase induction motor, except that the stator tends not toward synchronism but toward a definite speed equal to $(1 + c)$ times synchronism.

The speed of such a polyphase motor with commutator can, therefore, be varied from synchronism by the insertion of an e.m.f. in the rotor circuit, and the percentage of variation is the same as the ratio of the impressed motor e.m.f. to the impressed stator e.m.f. A rotor e.m.f. in opposition to the stator e.m.f. reduces, in phase with the stator e.m.f. increases the free running speed of the motor. In the former case the rotor impressed e.m.f. is in opposition to the rotor current, that is the rotor returns power into the system in the proportion in which the speed is reduced, and the speed variation, therefore, occurs without loss of efficiency, and is similar in its character to the speed control of a direct-current shunt motor by varying the ratio between the e.m.f. impressed upon the armature and that impressed upon the field.

Substituting in the equations:

$$\left.\begin{aligned} \omega &= o \\ s + c &= s_1 \end{aligned}\right\} \tag{17}$$

it is:

$$I_0 = E_0 \frac{{}_1Z + Z_1}{s\,ZZ_0 + ZZ_1 + Z_0 Z_1} \tag{18}$$

$$I_1 = E_0 \frac{s_1\, Z}{s\,ZZ_0 + ZZ_1 + Z_0 Z_1} \tag{19}$$

$$P = \frac{a\, e_0^2\, z^2\, s_1\,(r_1 - c r_0)}{[s\,ZZ_0 + ZZ_1 + Z_0 Z_1]^2} \tag{20}$$

These equations are very similar to the polyphase **induction** motor equations.

The stator current:

$$I_0 = E_0 \frac{s\,Z + Z_1 + \delta\, c\, Z}{s\,ZZ_0 + ZZ_1 + Z_0 Z_1}$$

can be resolved into a component:

$$I_0^1 = E_0 \frac{s\,Z + Z_1}{s\,ZZ_0 + ZZ_1 + Z_0\, Z_1} \tag{21}$$

which does not contain c, and is the same value as the primary current of the polyphase induction motor, and a component:

$$I_0^{11} = E_0 \frac{\delta\, c\, Z}{s\,ZZ_0 + ZZ_1 + Z_0 Z_1} \tag{22}$$

Resolving I_0^{11}, it assumes the form:

$$I_0^{11} = E_0 \delta\, c(A_1 + jA_2)$$
$$= c\{A_1 \cos \omega + A_2 \sin \omega) - j\,(A_1 \sin \omega - A_2 \cos \omega)\}$$

Hence, by choosing:

$$A_1 \cos \omega + A_2 \sin \omega = o$$

or:

$$\tan \omega = -\frac{A_1}{A_2} \qquad (23)$$

it is:

$$I_0^{11} = j\,c\,\sqrt{A_1^2 + A_2^2} = \frac{j\,c\,zE_0}{[s\,ZZ_0 + ZZ_1 + Z_0 Z_1]} \qquad (24)$$

Hence this component can, by choosing ω, be made wattless, and by choosing c, any desired positive or negative, that is lagging or leading value, can be given to it. The wattless lagging component of I_0 can, therefore, be compensated by a leading value of I_0^{11}, that is unity power factor produced, or overcompensated, that is the main current made leading.

If:

$$I^1_0 = i_0^1 + j i_0^{11},$$
$$c = -\frac{i_0^{11}}{z}[s\,ZZ_0 + ZZ_1 + Z_0 Z_1] \qquad (25)$$

gives unity power factor, higher values of c give leading, lower lagging current, and by varying c, a phase characteristic of the polyphase shunt motor can be produced, closely resembling the V-shaped phase characteristic of the synchronous motor produced by varying its field excitation.

Such phase characteristics of polyphase shunt motors have been observed.

In the exact predetermination of the characteristics of such a motor, the effect of the short-circuit current under the brushes has to be taken into consideration, however. When a commutator is used, by the passage of the brushes from segment to segment coils are short-circuited. Therefore, in addition to the circuits considered above, a closed circuit on the rotor has to be introduced in the equations for every set of brushes. Reduced to the stator circuit by the ratio of turns, the self-inductive impedance of the short-circuit under the brushes is very high, the current, therefore, small, but still sufficient to noticeably affect the motor characteristics, at least at certain speeds. Since, however, this phenomenon

will be considered in the chapters on the single-phase series and repulsion motors, it may be omitted here.

(5) *Polyphase Series Motor.*

If in a polyphase commutator motor the rotor circuits are connected in series to the stator circuits, entirely different characteristics result, and the motor no more tends to synchronise, as the induction motor with short-circuited secondary, nor approaches a definite speed at no load, as a shunt motor, but with decreasing load the speed increases indefinitely. In short, the motor has similar characteristics as the direct-current series motor. In this case, as in the following investigations of single-phase alternating-current motors, we may

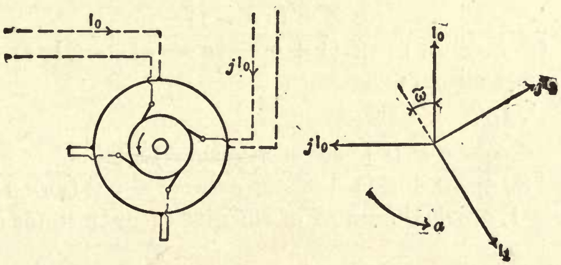


FIG. 8.— POLYPHASE SERIES MOTOR.

assume the stator reduced to the rotor by the ratio of effective turns.

Let then, in the motor shown diagrammatically in Fig. 8:

E_0 and jE_0, I_0 and jI_0, Z_0 = impressed e.m.f's., currents and self-inductive impedance of stator circuits, assumed as two-phase, and reduced to the rotor circuits by the ratio of effective turns, c,

E_1 and jE_1, I_1 and jI_1, Z_1 = impressed e.m.f's. currents and self-inductive impedance of rotor circuits,

Z = mutual-inductance impedance,

a = speed and: $s = 1 - a$ = slip,

ω = brush angle,

c = ratio of effective stator turns to rotor turns.

If then:

E and jE = impressed e.m.f's., I and jI = currents of motor, it is:

$$I_1 = I \tag{1}$$

$$I_0 = cI \tag{2}$$

$$cE_0 + E_1 = E \tag{3}$$

and, stator:

$$E_0 = Z_0\, I_0 + Z\, (I_0 - I_1 \cos \omega + jI_1 \sin \omega) \tag{4}$$

rotor:

$$E_1 = Z_1\, I_1 + Z\, (I_1 - I_0 \cos \omega - jI_0 \sin \omega) + j\, a\, Z\, (jI_1 + I_0 \sin \omega - jI_0 \cos \omega) \tag{5}$$

and, e.m.f. of rotation:

$$E_1^1 = j\, a\, Z\, (jI_1 + I_0 \sin \omega - jI_1 \cos \omega) \tag{6}$$

Substituting (1), (2) in (4), (5), (6), and (4), (5) in (3), gives:

$$I = \frac{E}{(c^2 Z_0 + Z_1) + Z (1 + c^2 - 2c \cos \omega) + a\, Z\, (c\, \sigma - 1)} \tag{7}$$

where:

$$\sigma = \cos \omega + j \sin \omega \tag{8}$$

and:

$$E_1^1 = \frac{a\, Z\, E\, (c\, \sigma - 1)}{(c^2\, Z_0 + Z_1) = Z\, (1 + c^2 - 2c \cos \omega) + a\, Z\, (c\, \sigma - 1)} \tag{9}$$

and the power output:

$$P = /E_1^1, I_1/^1$$

$$= \frac{a\, e^2 \{c\, (r \cos \omega + x \sin \omega) - r\}}{[(c^2 Z_0 + Z_1) + Z\, (1 + c^2 - 2\, c \cos \omega) + a\, Z\, (c\, \sigma - 1)]^2} \tag{10}$$

For: $c = 1$, or equal number of effective turns in stator and rotor, it is:

$$I = \frac{E}{Z_0 + Z_1 + 2\, Z\, (1 - \cos \omega) + a\, Z\, (\sigma - 1)} \tag{11}$$

$$P = \frac{a\, e_2\, (r \cos \omega + x \sin \omega - r)}{[Z_0 + Z_1 + 2\, Z\, (1 - \cos \omega) + a\, Z\, (\sigma - 1)]^2} \tag{12}$$

The characteristics of this motor entirely vary with a change of the brush angle ω. It is, for: $\omega = \sigma : P = \frac{ae^2 r\, (c - 1)}{[D]^2}$, hence very small, while for $\omega = 90° : P = \frac{ae^2\, (xc - r)}{[D]^2}$, hence considerable. Some brush angles give positive P: motor, others negative P: generator.

Substituting in (7) for Z, etc., it is:

$$I = \frac{E}{\{c^2 r_0 + r_1 + r\, (1 + c^2 - 2\, c \cos \omega) + a\, (c(r \cos \omega + x \sin \omega) - r)\} - j \{c^2 x_0 + x_1 + x\, (1 + c^2 - 2\, c \cos \omega) + a\, (c(x \cos \omega - r \sin \omega) - x)\}} \tag{13}$$

hence the angle of lag of the current input behind the impressed e.m.f. is given by:

$$\tan \varphi = \frac{c^2 x_0 + x_1 + x\,(1 + c^2 - 2\,c \cos\,\omega) + a\,(c\,x \cos\,\omega - r \sin \omega) - x)}{c^2 r_0 \;\; + r_1 + r\,(1 + c^2 - 2\,c \cos\,\omega) + a\,(c(r \cos\,\omega + x \sin\,\omega) - r)}. \qquad (14)$$

In such a motor, by choosing ω and c, appropriately unity power factor or leading current as well as lagging current can be produced. The limits of this paper, however, do not permit a further discussion of the very interesting characteristics derived by choosing different values of c and ω in polyphase as well as single-phase shunt and series motors, and an investigation of the effect of the short-circuit current under the commutator brushes.

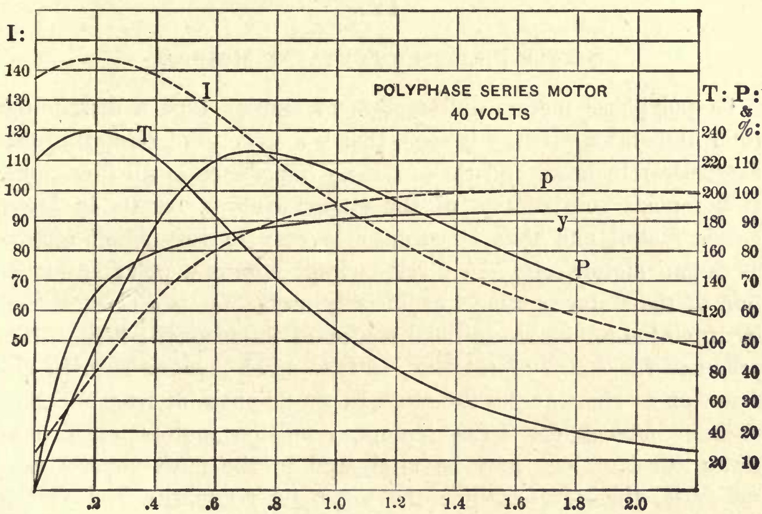


FIG. 9.

As instance as shown in Fig. 9, with the speed as abscissæ, and values from standstill to over double synchronous speed, the characteristic curves of a polyphase series motor of the constants:

$e = 640$ volts

$Z = 1 - 10\,j$ ohms

$Z_0 = Z_1 = .1 - .3\,j$ ohms

$c = 1$

$\omega = 37^{\circ}$ ($\sin \omega = .6$; $\cos \omega = .8$)

hence:

$$I = \frac{640}{(.6 + 5.8a) - j(4.6 - 2.6a)} \text{ amps.}$$

$$P = \frac{4673a}{(.6 + 5.8a)^2 + (4.6 - 2.6a)^2} \text{ kw.}$$

As seen, the motor characteristics are similar to those of the direct-current series motor: very high torque in starting and at low speed, and a speed, which increases indefinitely with the decrease of load. That is the curves are entirely different from those of the induction motors shown in the preceding. The power factor is very high, much higher than in induction motors, and becomes unity at the speed: $a = 1.77$, or about one three-quarter synchronous speed.

IV.

Single-Phase Commutator Motors.

In polyphase motors and motors of similar type a distributed rotor and stator winding is used, that is a structure having uniform magnetic reluctance and thus exciting impedance in all directions, and a polar construction of the stator winding results in lower power factor, and thus is permissible only in very small motors — as fan motors, etc. In direct-current motors a polar construction of the stator is almost exclusively used, that is a construction in which the reluctance in the direction of the magnetic field, which produces the e.m.f. of rotation, is very much smaller than in the direction at right angles thereto. In single-phase alternating commutator motors (as series motors, repulsion motors, etc.) both stator constructions may be used, and in the most general case we must, therefore, assume the magnetic reluctance and so the exciting impedance in the direction of the axis of the rotor circuits Z' as different from the exciting impedance Z at right angles to this axis. When different, the latter Z is usually far larger than the former Z', since Z is in the direction of the magnetic flux which produces the e.m.f. of rotation, that is corresponds to the field excitation, while in the direction of Z' energy transfer between stator and rotor, or compensation of rotor reaction takes place, but magnetic flux in the direction Z' does not produce e.m.f. and thereby power by the rotation of the motor.

The stator winding can, therefore, be considered as consisting

of two components, or may be constructed of two separate circuits, in the directions in line and at right angles to the rotor winding, which circuits may be connected in series or energized in any other manner, as, for instance, by exciting one by the impressed e.m.f., short-circuiting the other upon itself, etc. With a completely distributed winding and an angle ω between the axes of the stator and the rotor circuits (the angle of brush position), the exciting or magnetizing component of the stator winding is $I_0 \sin \omega$, the compensating or power transferring component $I_0 \cos \omega$ if $I_0 =$ stator current, as shown in diagram Fig. 10. When using separate circuits for the two stator components, they can even magnetically be arranged differently, as, for instance, a unitooth or polar arrangement chosen for the field exciting circuit, a dis-

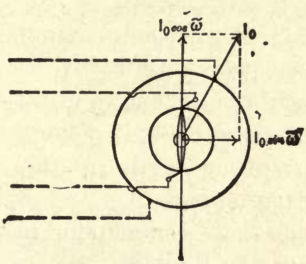


FIG. 10.

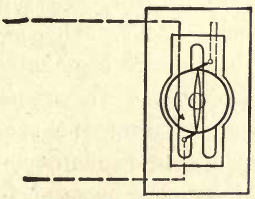


FIG. 11.—SINGLE-PHASE SERIES MOTOR.

tributed winding for the compensating circuit. In this case obviously, when reducing all circuits to each other by the ratio of effective turns, the resultant vector of the distributed winding has to be used.

As limit case, with zero compensating winding, appears the plain uncompensated series motor, consisting of a polar field exciting circuit and an armature with brushes at the neutral or at right angles to the field, as shown in Fig. 11; as a further limit case, a motor with zero field exciting winding on the stator and excitation of the rotor by a second system of brushes at right angles to the main or power brushes, as shown diagrammatically in Fig. 12.

In alternating-current commutator motors, especially of the single-phase type, the short-circuit current in the coils under the brushes during commutation has to be taken into consideration. While with numerous commutator segments, carbon brushes and possibly an additional resistance in the commutator leads, as

occasionally used in such motors, these short-circuit currents may be moderate, they still are sufficient to noticeably affect the constants of the motor, especially at high speeds, where the main current is small, and at standstill, where the main magnetic flux is very large. Furthermore, the character of the commutation of

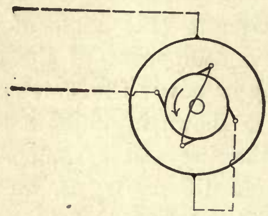


FIG. 12.— WINTER-EICHBERG-LATOUR MOTOR.

the motor, and, therefore, its operativeness, depends upon these currents. An excessive short-circuit current gives destructive sparking, while zero short-circuit current would be conducive to perfect commutation. In comparing different types of such motors, the investigation of the short-circuit current under the brushes is, therefore, of fundamental practical importance.

In its most general form, the single-phase commutator motor can thus be represented diagrammatically by Fig. 13.

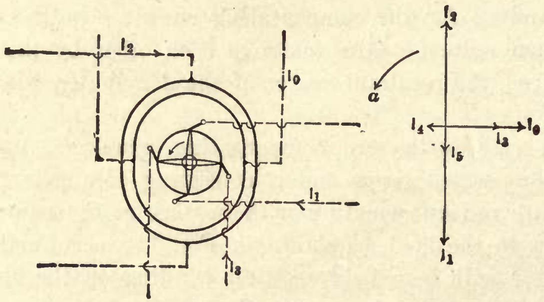


FIG. 13.

Let: E_0, I_0, Z_0 = impressed e.m.f. current and self-inductive impedance of magnetizing or exciter circuit of stator (field coils), reduced to the rotor energy circuit by the ratio of effective turns c,

E_1, I_1, Z_1 = impressed e.m.f., current and self-inductive impedance of rotor energy circuit (or circuit at right angles to I_0),

E_2, I_2, Z_2 = impressed e.m.f., current and self-inductive imped-

ance of stator compensating circuit (or circuit parallel to I_1; the "cross-coil" of the Eickemeyer motor), reduced to the rotor circuit by the ratio of effective turns b,

E_3, I_3, Z_1 = impressed e.m.f., current and self-inductive impedance of the exciting circuit of the rotor, or circuit parallel to I_0,

I_4, Z_4 = current and self-inductive impedance of the short-circuit under the brushes I_1, reduced to the rotor circuit,

I_5, Z_5 = current and self-inductive impedance of the short-circuit under the brushes I_3, reduced to the rotor circuit,

Z = mutual impedance of field excitation, that is in the direction of I_0, I_3, I_4,

Z^1 = mutual impedance of armature reaction, that is, in the direction of I_1, I_2, I_5.

Z^1 usually either equals Z, or is much smaller than Z,

I_4 and I_5 are very small, Z_4 and Z_5 very large quantities.

Let: a = speed, as fraction of synchronism.

The equations of the six circuits now are:

$$E_0 = Z_0 I_0 + Z\ (I_0 + I_3 - I_4). \tag{1}$$
$$E_1 = Z_1 I_1 + Z^1\ (I_1 + I_5 - I_2) + j\,a\,Z\ (I_0 + I_3 - I_4) \tag{2}$$
$$E_2 = Z_2 I_2 + Z^1\ (I_2 - I_1 - I_5). \tag{3}$$
$$E_3 = Z_1 I_3 + Z\ (I_3 + I_0 - I_4) + j\,a\,Z^1\ (I_2 - I_1 - I_5). \tag{4}$$
$$o = Z_4 I_4 + Z\ (I_4 - I_0 - I_3) + j\,a\,Z^1\ (I_1 + I_5 - I_2). \tag{5}$$
$$o = Z_5 I_5 + Z^1\ (I_5 + I_1 - I_2) + j\,a\,Z\ (I_0 + I_3 - I_4). \tag{6}$$

Substituting:

$Z^1/Z = A$, where $A = 1$ with a motor of uniform reluctance, (7)

$$\left.\begin{aligned} Z/Z_4 &= \lambda_4 \\ Z/Z_5 &= \lambda_5 \end{aligned}\right\} \tag{8}$$

where λ_4 and λ_5 are small quantities, and suppressing terms of secondary order, equations (5) and (6) give:

$$I_4 = \lambda_4 \{ (I_0 + I_3) + j\,a\,A\,(I_2 - I_1) \} \tag{9}$$
$$I_5 = \lambda_5 \{ (I_2 - I_1) - j\,a\,A\,(I_0 + I_3) \} \tag{10}$$

Substituting (9) and (10) into (1), (2), (3), (4), gives four equations containing the eight quantities: E_0, E_1, E_2, E_3, I_0, I_1, I_2, I_3, requiring four further conditions to be given, which are the conditions of operation of the four circuits, and distinguish the different types or modifications of such single-phase alternating-current motors.

Some of the types under practical considerations at present are:

(1.) Series Motor:

$$E = cE_0 + E_1;\ I_0 = cI_1;\ I_2 = o;\ I_3 = o.$$

(2.) Compensated Series Motor (Eickemeyer Motor).

(a.) direct compensation:

$$E = cE_0 + E_1 + bE_2;\ I_0 = cI_1;\ I_2 = bI_1;\ I_3 = o.$$

(b.) inductive compensation:

$$E = cE_0 + E_1;\ E_2 = o;\ I_0 = cI_1;\ I_3 = o.$$

(3.) Repulsion Motor (Thomson Motor):

$$E = cE_0 + bE_2;\ E_1 = o;\ cI_0 = bI_2;\ I_3 = o.$$

(4.) Compensated Repulsion Motor (Winter-Eichberg-Latour Motor):

$$E = bE_2 + fE_3;\ E_1 = o;\ I_0 = o;\ bI_2 = fI_3.$$

(5.) Inverted Series Motor:

$$E = E_1 + bE_2 + fE_3;\ I_0 = o;\ I_2 = bI_1;\ I_3 = fI_1.$$

(6.) Inverted Repulsion Motor:

$$E = E_1;\ cE_0 + bE_2 = o;\ cI_0 = bI_2;\ I_3 = o.$$

(7.) Induced Series Motor:

$$E = E_2;\ E_1 + cE_0 = o;\ cI_0 = I_1;\ I_3 = o.$$

Types (4.) and (5.) have two sets of brushes on the rotor.

In types (3.) and (7.), the rotor is not connected to the external or supply circuit, and its voltage can, therefore, be chosen independent of the supply voltage; in type (4.), by feeding circuit E_3 through transformer, the same may be secured.

Frequently in motors of uniform reluctance: $Z^1 = Z$, as the two stator circuits I_0 and I_2 the two parts of the same uniformly distributed circuit are used, and then $c/b = \tan \omega$, where $\omega =$ angle of brush shift.

Only a few of the more important types can be discussed in the following:

(1.) *Single-phase Series Motor.*

The plain or uncompensated single-phase series motor is usually designed with definite field poles, similar to the direct-current series motor (only that the field is laminated also). The object of the polar construction is to secure as low a value of Z^1 and as high a value of Z as possible, so as to reduce the armature self-induction which is not compensated, and secure a fair power factor.

Let then, in the motor shown diagrammatically in Fig. 14:

$E =$ impressed e.m.f., $I =$ current, $c =$ ratio of effective field turns to effective armature turns;

E_0, I_0, Z_0, $Z =$ impressed e.m.f., current, self-inductive and mutual-inductive impedance of field circuit, reduced to armature circuit;

E_1, I_1, Z_1, Z^1 = impressed e.m.f., current, self-inductive and mutual-inductive impedance of armature circuit;

I_4, Z_4 = current and self-inductive impedance of the short-circuit under the brush, reduced to the armature circuit.

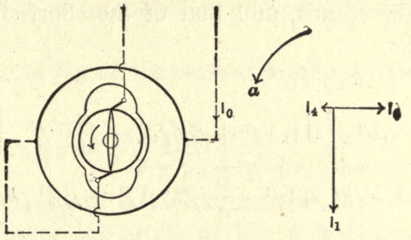


FIG. 14.—SINGLE-PHASE SERIES MOTOR.

a = speed.

$Z/Z_4 = \lambda = \lambda_1 - j\lambda_2 \quad Z^1/Z_4 = \lambda^1 = \lambda_1^1 - j\lambda_2^1$

It is then:

$$E = cE_0 + E_1 \qquad (1)$$

$$I_0 = cI \qquad (2)$$

$$I_1 = I \qquad (3)$$

$$E_0 = Z_0 I_0 + Z(I_0 - I_4) \qquad (4)$$

$$E_1 = Z_1 I_1 + Z^1 I_1 + jaZ(I_0 - I_4) \qquad (5)$$

$$O = Z_4 I_4 + Z(I_4 - I_0) + jaZ^1 I_1 \qquad (6)$$

Hence:

$$I_4 = I(\lambda c - ja\lambda^1) \qquad (7)$$

And:

$$I = \frac{E}{c^2(Z + Z_0) + (Z^1 + Z_1) + jacZ - Z(c + ja)(c\lambda - ja\lambda^1)}$$

$$= \frac{E}{c^2 Z_0 + Z_1 + Z^1 + Z(c + ja)(c(1 - \lambda) + ja\lambda^1)} \qquad (8)$$

Or, denoting:

$$D = c^2 Z_0 + Z_1 + Z^1 + Z(c + ja)(c(1 - \lambda) + ja\lambda^1) \qquad (9)$$

$$I = \frac{E}{D} \qquad (10)$$

$$I_4 = \frac{E(\lambda c - ja\lambda^1)}{D} \qquad (11)$$

The e.m.f. of rotation of the main circuit is:

$$E_1^1 = jaZ(I_0 - I_4)$$

$$= \frac{jacZE\left(1 - \lambda + j\frac{a}{c}\lambda^1\right)}{D} \qquad (12)$$

of the short-circuit under the brush:

$$E_4^1 = jaZ^1 I_1$$

$$= \frac{j a Z^1 E}{D} \qquad (13)$$

The power output of the motor is the algebraic sum of the power of the main rotor circuit, and that of the short-circuit under the brush, hence is:

$$P = /E_1^1, I/^1 + E_4^1, I_4/^1$$

$$= \frac{ace^2}{[D]^2} \left\{ /jZ(1 - \lambda + j\frac{a}{c}\lambda^1), 1/^1 + /jZ_1^1, \lambda - j\frac{a}{c}\lambda^1 /^1 \right\}$$

$$= \frac{ace^2}{[D]^2} \left\{ /jZ, 1/^1 - /jZ\,\lambda, 1/^1 - \frac{a}{c}/Z\lambda^1, 1/^1 + /jZ^1, \lambda/^1 - \frac{a}{c}/Z^1, \lambda^1/^1 \right\}$$

and since:

$$/jZ,\ 1/^1 = x$$
$$/jZ\lambda,\ 1/^1 = x\lambda_1 + r\lambda_2$$
$$/Z\lambda^1,\ 1/^1 = r\lambda_1^1 - x\lambda_2^1$$
$$/jZ^1,\ \lambda/^1 = x^1\lambda_1 - r^1\lambda_2$$
$$/Z^1,\ \lambda^1/^1 = r^1\lambda_1^1 + x^1\lambda_2^1$$

it is:

$$P = \frac{acxe^2}{[D]_2} \left\{ 1 - \frac{1}{x}\Big((x - x^1)\lambda_1 1 + (r + r^1)\lambda_2 + \frac{a}{c} (r + r^1)\lambda_1^1 - \frac{a}{c}(x - x^1)\lambda_2^1 \Big) \right\} \qquad (14)$$

and the torque:

$$T = \frac{P}{a} = \frac{c x e^2}{[D]^2} \left\{ 1 - \frac{1}{x}\Big((x - x^1)\lambda_1 + (r + r^1)\lambda_2 + \frac{a}{c} (r + r^1)\lambda_1^1 - \frac{a}{c}(x - x^1)\lambda_2^1 \right\}\Big) \qquad (15)$$

In the equation of the current (8),
$c^2\ (Z_0 + Z)$ is the total impedance of the field,
$Z_1 + Z^1$ is the total impedance of the armature, hence:
$c^2\ (Z_0 + Z) + (Z_1 + Z^1)$ is the total impedance of the motor, corresponding to the e.m.f. consumed by the effective resistance and the self-induction of field and armature,
$jacZ$ corresponds to the e.m.f. of rotation, or the mechanical work done by the motor, and
$Z\ (c + ja)\ (c\lambda - ja\lambda^1)$ is the effect of the short-circuit current under the commutator brush.

Neglecting the short-circuit current of commutation, as of secondary order, it is:

$$\left.\begin{aligned} I &= \frac{E}{c^2(Z+Z_0)+(Z^1+Z_1)+jaZ} \\ &= \frac{E}{\left\{c^2(r+r_0)+(r^1+r_1)+acx\right\}-j\left\{c^2(x+x_0)+(x^1+x_1)-acr\right\}} \end{aligned}\right\} \quad (16)$$

hence, the angle of lag of the current I behind the impressed e.m.f. E is given by:

$$\tan\varphi = \frac{c_2(x+x_0)+(x^1+x_1)-acr}{c^2(r+r_0)+(r^1+r_1)+acx} \quad (17)$$

With increasing speed a, the numerator decreases, the denominator increases, hence the angle of lag ϕ decreases and the power factor $\cos\phi$ increases.

The power factor of the motor becomes unity, or $\phi = o$, at the speed:

$$a = \frac{c^2(x+x_0)+(x^1+x_1)}{cr} \quad (18)$$

That is at some very high speed the power factor of the single-phase alternating-current series motor, even if not compensated, would become unity, if there were no commutation losses.

On first sight this is unexpected, since even assuming the armature as entirely non-inductive, in addition to the e.m.f. induced in the armature by the rotation through the alternating magnetic field, and in phase thereto, in the field coils a quadrature e.m.f. must be induced by the same magnetic flux, and while the former increases relatively to the latter with the speed, the quadrature e.m.f. obviously never can become zero.

The explanation is found in the following: In equation (17) the denominator contains the effective exciting resistances r as factor, which represents the hysteretic loss in the motor, and if $r = o$, or no hysteresis loss, unity power factor would be reached only at infinite speed. Due to the hysteresis loss in the alternating magnetic field, when considering equivalent sine waves, the magnetic flux lags behind the magnetizing current by the angle of hysteretic lag α, and the e.m.f. of rotation, which is in phase with the magnetic flux, therefore, lags behind the current, that is the current leads the e.m.f. of rotation, and so at a certain definite speed compensation for the lag due to the e.m.f. of self-induction in the motor takes place by the lead of the e.m.f. of rotation ahead of the magnetizing current, which in this case is the main current

of the motor. This feature is found in nearly all types of single-phase commutator motors, that is at a certain high speed, when neglecting commutation losses, the current is in phase with the impressed e.m.f. (and at still higher speed leading), and when considering equivalent sine waves the power factor is unity. Considering the actual wave shape, however, there remains a wattless component which represents the wave-shape distortion caused by the hysteretic cycle of the magnetic field. It also follows that in all such single-phase commutator motors a certain wave-shape distortion must take place, since the e.m.f. of rotation is of the same wave shape as the magnetic field flux, but the magnetic field flux and the current differ in wave shape by the wave-shape distortion represented in the hysteretic cycle of the magnetic structure.

At given speed a, the power factor is a maximum for that value of c, where:

$$\frac{d}{dc}(\tan \varphi) = o$$

substituting (17), and suppressing quantities of higher order, this gives:

$$c = \frac{rx^1 + xr^1}{az^2} + \sqrt{\frac{xx^1 + rr^1}{z^2} + \left(\frac{rx^1 - xr^1}{az^2}\right)^2}$$

or approximately, for higher speeds a:

$$c = \sqrt{\frac{xx^1 + rr^1}{z}} \qquad (20)$$

Since $Z^1 < Z$, condition of good power factor of an uncompensated single-phase series motor is: $c < 1$, that is, low field excitation and high armature reaction. Let, for instance, $Z = 1 - 10j$, $Z^1 = .25 - 2.5j$, it is: $c = .5$, or the number of effective armature turns equals twice the number of effective field turns.

As an instance are shown, in Fig. 15, with the speed a as abscissæ, and for values up to above double synchronism, the characteristic curves of a single-phase series motor of the constants:

$e = 800$ volts.
$Z = 1 - 10j$ ohms
$Z^1 = .25 - 2.5j$ ohms
$Z_1 = .1 - .3j$ ohms
$Z_0 = .4 - 1.2j$ ohms
$Z_4 = 30 - 30j$ ohms, hence: $\lambda = .18 - .15j$; $\lambda^1 = .045 - .038j$
$c = .5$

hence:

$$I = \frac{800}{(1.03 + 4.27a + .35a^2) - j(5.19 - .98a - .49a^2)}$$

$$P = \frac{640a\,(4.23 + .25a)}{(1.03 + 4.27a + .35a^2)^2 + (5.19 - .98a - .49a^2)^2}$$

As seen, at very high speeds, power factor p and efficiency y reach very good values.

The curves are similar to those of the direct-current series motor, except that with increasing speed, current, torque and power fall

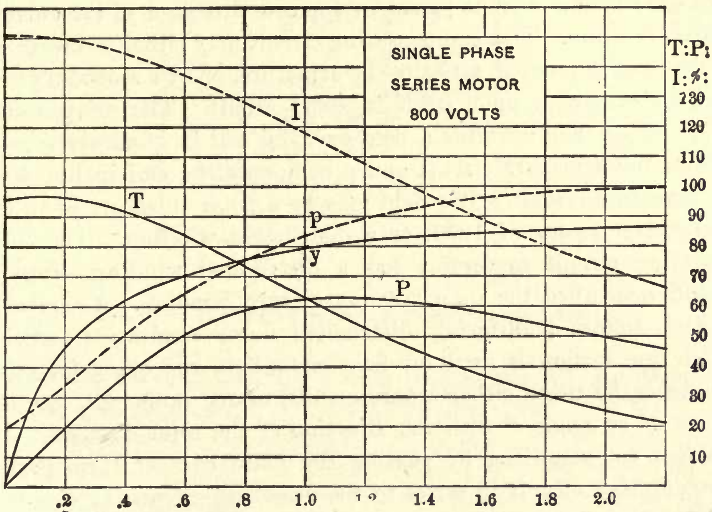


FIG. 15.

off rather slower, that is, the motor tends more toward racing at light load.

(2) *Compensated Series Motor* (*Eickemeyer Motor*).

To secure good power factors in a single-phase series motor, a low field self-inductance, that is low number of field exciting turns, is necessary, and, therefore, a high number of armature turns, to get the required output. Increasing the ratio of the armature reaction to field excitation, a limit is reached, where the increase of armature self-inductance overbalances the decrease of field inductance, and the power factor again decreases. In the preceding instance shown in Fig. 15 this limit is reached at an armature

reaction equal to about twice the field excitation, and at this proportion the power factor is highest, but still rather poor at low and moderate speeds. Better proportions may possibly be reached by different design, but in this feature the limitation of the plain series motor is found: in the limited armature reaction permissible by armature self-induction. By compensating for the armature reaction and so more or less completely neutralizing its self-induction, a higher ratio of armature reaction to field excitation and so better power factors may be secured. The armature self-induction is compensated by surrounding the armature by a stationary circuit, through which a current passes in opposite direction to the current in the armature. This compensating circuit may either be energized by the main current in series to the armature, or by a secondary current, by closing it upon itself in short-circuit. The compensated series motor then contains a field exciting coil in quadrature position to the armature circuit and a compensating coil in line with the armature circuit. The field may be a polar structure as in the Eickemeyer motor of 1890, or a distributed winding. The compensating circuit preferably has a distributed winding, since it should neutralize the distributed armature winding. Frequently in such motors a uniformly distributed stator winding is used, of which one section is used for field excitation, the other for compensation, by using either separate coils, or the same coil, tapping into it at an angle ω with the direction of the rotor circuit.

When compensating by passing the main current through the compensating circuit in series to the armature circuit, by choosing the number of turns of the compensating circuit, under-compensation, or overcompensation, or complete compensation can be secured. Complete compensation obviously gives the best power factor. Some valuable features, however, are produced by overcompensation.

When compensating by closing the compensating circuit upon itself, as secondary short-circuit, the compensation necessarily is always approximately complete.

(*a*) *Directly Compensated Motor.*

Let in the motor shown diagrammatically in Fig. 16:

$E =$ impressed e.m.f., $I =$ current of the motor,

E_0, I_0, $Z_0 =$ impressed e.m.f., current and self-inductive impedance of field exciting circuit, reduced to the armature circuit by the ratio c of effective field turns to effective armature turns,

E_1, I_1, Z_1 = impressed e.m.f., current and self-inductive impedance of armature circuit,

E_2, I_2, Z_2 = impressed e.m.f., current and self-inductive impedance of (stationary) compensating circuit, reduced to the armature circuit by the ratio of effective turns b,

I_4, Z_4 = current and self-inductive impedance of the short-circuit under the commutator brush, reduced to the armature circuit,

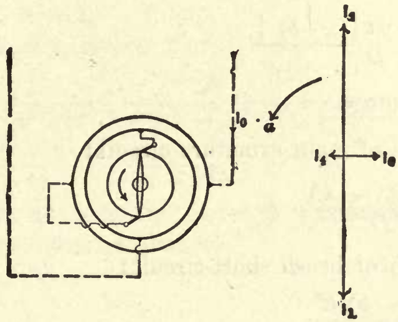


FIG. 16.—EICKEMEYER MOTOR DIRECT COMPENSATION.

Z = mutual-inductive impedance, constant in all directions,

$Z/Z_4 = \lambda = \lambda_1 - j\lambda_2$.

a = speed.

It is then:

$$E = E_1 + cE_0 + bE_2 \quad (1)$$

$$I_0 = cI \quad (2)$$

$$I_1 = I \quad (3)$$

$$I_2 = bI \quad (4)$$

Field circuit:

$$E_0 = Z_0 I_0 + Z(I_0 - I_4) \quad (5)$$

Compensating circuit:

$$E_2 = Z_2 I_2 + Z(I_2 - I_1) \quad (6)$$

Armature circuit:

$$E_1 = Z_1 I_1 + Z(I_1 - I_2) + jaZ(I_0 - I_4) \quad (7)$$

Brush short-circuit:

$$o = Z_4 I_4 + Z(I_4 - I_0) + jaZ(I_1 - I_2) \quad (8)$$

Herefrom follows:

$$I_4 = \lambda I \{ c - ja(1 - b) \} \quad (9)$$

$$= \lambda c I \text{ approximately} \quad (10)$$

Main current:

$$I = \frac{E}{\{c_2 Z_0 + Z_1 + b^2 Z_2 + Z(1-b)^2\} + c Z (c + ja)(1-\lambda)} \quad (11)$$

$$= \frac{E}{D} \quad (12)$$

where:

$$D = \{c^2 Z_0 + Z_1 + b^2 Z_2 + Z(1-b)^2\} + cZ(c+ja).(1-\lambda) \quad (13)$$

Short-circuit current under brushes:

$$I_4 = \frac{\lambda E \{c - ja(1-b)\}}{D} \quad (14)$$

$$= \frac{\lambda c E}{D} \text{ approx.} \quad (15)$$

e.m.f. of rotation of main armature circuit:

$$E_1^1 = \frac{jacZE(1-\lambda)}{D} \quad (16)$$

e.m.f. of rotation of brush short-circuit:

$$E_4^1 = \frac{jaZ(1-b)E}{D} \quad (17)$$

Power output:

$$P = /E_1^1, I/^1 + /E_4^1, I_4/^1.$$

$$= \frac{ace^2}{[D]^2} \{/jZ(1-\lambda), 1/^1 + /jZ(1-b), \lambda/^1\}$$

$$= \frac{ac\, xe^2}{[D]^2} \left\{ 1 - b\lambda_1 - (2-b)\frac{r}{x}\lambda_2 \right\} \quad (18)$$

Torque:

$$T = \frac{cxe^2}{[D]^2} \left\{ 1 - b\lambda_1 - (2-b)\frac{r}{x}\lambda^2 \right\} \quad (19)$$

In the equation of the current, (11), $c^2(Z_0 + Z)$ is the total impedance of the field, $b^2 Z_2$ is the total impedance of the compensating circuit, $Z_1 + Z(1-b)^2$ is the total impedance of the armature, the component $Z(1-b)^2$ being due to incomplete compensation. In the uncompensated motor on its place stands Z^1.

Neglecting the effect of the short-circuit under the brush in equation (11), and substituting for Z, etc., it is:

$$I = \frac{E}{\{c^2(r_0 + r) + b^2 r_2 + r_1 + (1-b)^2 r + acx\} - j\{c^2(x_0 + x) + b^2 x_2 + x_1 + (1-b)^2 x - acr\}} \quad (20)$$

hence the angle of lag of the motor:

$$\tan \varphi = \frac{c^2(x_0+x)+b^2x_2+x_1+(1-b)^2x-acr}{c^2(r_0+r)+b^2r_2+r_1+(1-b)^2r+acx} \tag{21}$$

$\phi = o$, that is, unity power factor is reached at the speed:

$$a = \frac{c^2(x_0+x)+b^2x_2+x_1+(1-b)^2x}{cr} \tag{22}$$

The explanation hereof is the same as in the preceding chapter.

The term $(1-b)^2 Z$ disappears, that is, complete compensation takes place for: $b = 1$.

Substituting $b = 1$, gives:

$$I = \frac{E}{\{c^2(r_0+r)+r_2+r_1+acx\} - j\{c^2(x_0+x)+x_2+x_1-acr\}}$$

$$\tan \varphi = \frac{c^2(x_0+x)+x_2+x_1-acr}{c^2(r_0+r)+r^2+r_1+acx}$$

At given speed a, the power factor is a maximum, that is, ϕ a minimum, for the value of c, where:

$$\frac{d}{dc}(\tan \varphi) = o$$

this gives:

$$c = \frac{rx_2-xr_2}{az^2} + \sqrt{\frac{xx_2+rr_2}{z_2} + \left(\frac{rx_2-xr_2}{az^2}\right)^2} \tag{23}$$

or approximately, for higher values of a:

$$c = \frac{\sqrt{xx_2+rr_2}}{z} \tag{24}$$

Since the self-inductive impedance Z_2 is very small compared with the exciting impedance Z, c is a small fraction, that is, the armature reaction of the completely compensated motor can be made very much higher than the field excitation. For instance, let: $Z = 1 - 10j$; $Z_2 = .13 - .4j$, it is: $c = .2$.

The e.m.f. of rotation of the short-circuited coil under the brush:

$$E_4{}^1 = \frac{jaZ(1-b)E}{D} \tag{17}$$

contains the factor $(1-b)$, hence disappears at complete compensation, $b = 1$, and reverses its direction by overcompensation: $b > 1$. Hence, by overcompensation a reverse e.m.f. can be inserted into the coil short-circuited under the brushes, and thereby the commutation controlled, that is, sparkless commutation secured, at the expense, however, of some decrease of the power factor.

As instance may be considered a motor of the constants:

$$e = 500 \text{ volts},$$
$$Z = 1 - 10j \text{ ohms},$$
$$Z_1 = .1 - .3j \text{ ohms},$$
$$Z_2 = .13 - .4j \text{ ohms},$$
$$Z_0 = .4 - 1.2j \text{ ohms},$$
$$Z_4 = 30 - 30j \text{ ohms},$$

hence: $\lambda = .18 - .15j$

$c = .25$

hence:

$$I = \frac{500}{(.4 + 2.01a) - j\,(1.28 - .58a)}$$

$$P = \frac{502.5a}{(.4 + 2.01a)^2 + (1.28 - .58a)^2}$$

Since the curves of this motor are almost identical with those of the inductively compensated motor, they are not given.

(*b.*) *Inductively Compensated Motor.*

Let, in the motor shown diagrammatically in Fig. 17 the denotations be the same as in (*a.*), the directly compensated motor, except

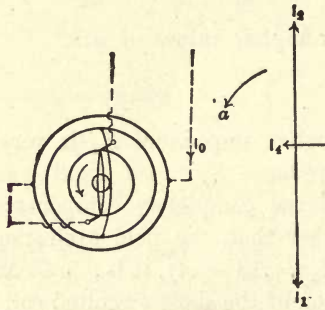


FIG. 17.— EICKEMEYER MOTOR INDUCTIVE COMPENSATION.

that now I_2 is a separate, secondary current, and not $= bI$, and $E_2 = o$. It is then:

$$E = E_1 + cE_0, \tag{1}$$
$$I_0 = cI, \tag{2}$$
$$I_1 = I, \tag{3}$$

Field circuit:

$$E_0 = Z_0 I_0 + Z\,(I_0 - I_4) \tag{4}$$

Armature circuit:

$$E_1 = Z_1 I_1 + Z \ (I_1 - I_2) + jaZ \ (I_0 - I_4) \tag{5}$$

Compensating circuit:

$$o = Z_2 I_2 + Z \ (I_2 - I_1)$$

Short-circuit under brush:

$$o = Z_4 I_4 + Z \ (I_4 - I_0) + jaZ \ (I_1 - I_2) \tag{7}$$

From (6) follows:

$$I_2 = \frac{Z}{Z + Z_2} I \tag{8}$$

from (7):

$$I_4 = \lambda I \left(c - ja \frac{Z_2}{Z + Z_2} \right) \tag{9}$$

hence substituted into equations (1) to (5):

Main current:

$$I = \frac{E}{c^2 Z_0 + Z_1 + \frac{Z Z_2}{Z + Z_2} + cZ \ (c + ja) \ (1 - \lambda)} \tag{10}$$

$$= \frac{E}{D} \tag{11}$$

where:

$$D = c^2 Z_0 + Z_1 + \frac{Z Z_2}{Z + Z_2} + cZ \ (c + ja) \ (1 - \lambda) \tag{12}$$

Short-circuit current under commutator brush:

$$I_4 = \frac{\lambda E \left(c - ja \frac{Z_2}{Z + Z_2} \right)}{D} \tag{13}$$

$$= \frac{\lambda c E}{D} \text{ approx.} \tag{14}$$

E.m.f. of rotation of main circuit:

$$E_1^1 = \frac{jacE \ (1 - \lambda)}{D} \tag{15}$$

E.m.f. of rotation of armature short-circuited coil:

$$E_4^1 = \frac{jaZ_2 E}{D} \tag{16}$$

hence very small.

Power output, suppressing terms of secondary magnitude:

$$P = \frac{acxe^2}{[D]^2} \left(1 - \lambda_1 - \frac{r}{x} \lambda_2 \right) \tag{17}$$

Torque:

$$T = \frac{cxe^2}{[D]^2} \left(1 - \lambda_1 - \frac{r}{x} \lambda_2 \right) \tag{18}$$

As seen, these equations contain: $\frac{ZZ_2}{Z+Z_2}$ instead of: $b^2 Z_2 + (1-b)^2 Z$ of the directly compensated motor, which latter, for $b=1$, gives Z_2. Since Z_2 is small compared with Z, $\frac{ZZ_2}{Z+Z_2}$ is almost identical with Z_2, inductive compensation gives almost identically the same results as complete direct compensation, and all conclusions derived under (a.) for the case of complete compensation: $b=1$, apply to the case of inductive compensation.

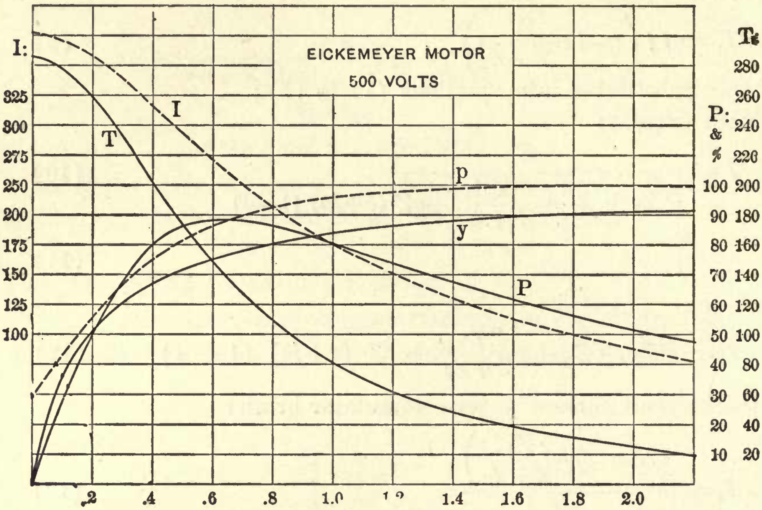


FIG. 18.

As instance are shown, in Fig. 18, with the speed a as abscissæ, the curves of an inductively compensated motor of the constants:

$e = 500$ volts,

$Z = 1 - 10j$ ohms,

$Z_1 = .1 - .3j$ ohms,

$Z_2 = .13 - .4j$ ohms,

$Z_0 = .4 - 1.2j$ ohms,

$Z_3 = 30 - 30j$ ohms, hence: $\lambda = .18 - .15j$

$c = .25$

Hence:

$$I = \frac{500}{(.39 + 2.01a) - j\,(1.27 - .58j)}$$

$$P = \frac{502.5a}{(.39 + 2.01a)^2 - (1.27 - .58)^2}$$

Interesting is the very high power factor reached already at low speed: 80 per cent below half synchronism. At speed: $a = 2.19$ unity power factor is reached.

The starting torque is very large, and with increase of speed the torque falls rapidly, very similar as in a direct-current series motor.

(3) *Repulsion Motor* (*Thomson Motor*).

In Prof. E. Thomson's single-phase repulsion motor the stator is supplied with the main current, the rotor short-circuited upon itself through the commutator brushes under an angle with the axis of the stator circuit.

Amongst the single-phase commutator motors this repulsion motor takes a separate and distinctive position by its magnetic characteristics and their effect on commutation, so that single-phase commutator motors may be divided into series motors and repulsion motors. While both types of motors have similar speed characteristics, the magnetic flux of the repulsion motor is an elliptically rotating flux, while that of the series motor is essentially an alternating flux. In the series motors treated in the preceding, the magnetic flux in the axis of the rotor circuit is either negligible, in the compensated motor, or as magnetic flux of armature reaction in phase with the main magnetic flux. The e.m.f. induced in the armature coil short-circuited under the brush, by its rotation, is, therefore, either negligible or in phase with the main flux, while that induced by the alternation of the flux enclosed by the short-circuited coil is in quadrature with the main flux, and so with the e.m.f. of rotation, and the short-circuited coil is the seat of an active e.m.f. at all speeds. In the repulsion motor, the magnetic flux in the direction of the axis of the armature circuit is in quadrature with the current and thereby the flux at right angles with the armature circuit, but the former is constant, the latter varying inversely with the speed. The e.m.f. induced by rotation in the coil short-circuited under the commutator brush is in phase with the quadrature field of the motor, while the e.m.f. of alternation is in quadrature with the main field, and since the two fields are in quadrature with each other, the two e.m.f's. induced in the short-circuited coil are in opposition to each other, that is neutralize each other more or less completely. At synchronism the two e.m.f's. are equal and opposite, the neutralization complete and commutation, therefore, theoretically perfect.

The repulsion motor can be constructed with distributed or with polar stator winding. Since, however, compensation takes place of the armature reaction by the primary current and the secondary current flowing in opposite direction, and the rotating m.m.f. of the motor can produce a uniformly revolving (circular or elliptic) magnetic field only in a structure of uniform reluctance, polar winding gives decidedly inferior characteristics and a distributed stator winding is, therefore, assumed in the following. With polar construction, different exciting impedances Z and Z^1 have to be introduced in the two quadrature directions.

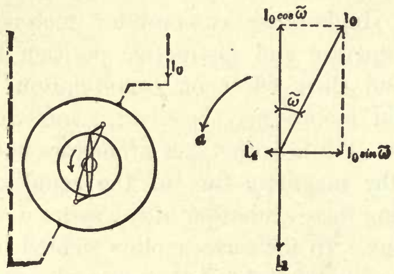


FIG. 19.—THOMSON MOTOR.

Let, in a repulsion motor:

E_0, I_0, Z_0 = impressed e.m.f., current and self-inductive impedance of primary or stator circuit,

I_1, Z_1 = current and self-inductive impedance of secondary or rotor circuit, reduced to primary by the ratio of effective turns,

I_4, Z_4 = current and self-inductive impedance of short-circuit under brush, reduced to primary circuit,

Z = mutual-inductive impedance,

$Z/Z_4 = \lambda = \lambda_1 - j\lambda_2$,

a = speed, as fraction of synchronism,

ω = angle between axis of primary and secondary circuit, or angle of brush shift.

It is then, in the motor shown diagrammatically in Fig. 19.

Stator:

$$E_0 = Z_0 I_0 + Z_0 \, (I_0 - I_1 \cos \omega - I_4 \sin \omega) \qquad (1)$$

Rotor:

$$o = Z_1 I_1 + Z_1 \, (I_1 - I_0 \cos \omega) + jaZ \, (I_0 \sin \omega - I_4) \qquad (2)$$

Short-circuit under brush:

$$o = Z_4 I_4 + Z_4 \ (I_4 - I_0 \sin \omega) + jaZ \ (I_1 - I_0 \cos \omega) \quad (3)$$

hence:

$$I_4 = \lambda \left\{ I_0 (\sin \omega + ja \cos \omega) - ja I_1 \right\} \quad (4)$$

and, substituting (4) in (2):

$$I_1 = I_0 Z \frac{(\cos a - ja \sin \omega) - a\lambda \ (a \cos \omega - j \sin \omega)}{Z + Z_1 - a_2 \lambda Z} \quad (5)$$

substituting (4) and (5) in (1):

$$I_0 = \frac{E_0}{Z} \frac{Z_1 + Z \ (1 - a_2 \lambda)}{Z_0 + Z_1 + Z \sin \omega \ (\sin \omega + ja \cos \omega) \ (1 - \lambda)} \quad (6)$$

or, denoting:

$$D = Z_0 + Z_1 + Z \ \sin \omega \ (\sin \omega + ja \ \cos \omega) \ (1 - \lambda) \quad (7)$$

Primary or main current:

$$I_0 = \frac{E_0 \left\{ Z_1 + Z \ (1 - a_2 \lambda) \right\}}{Z D} \quad (8)$$

Secondary current:

$$I_1 = E_0 \frac{\left\{ (\cos \omega - ja \sin \omega) - a\lambda \ (a \ \cos \omega - j \sin \omega) \right\}}{D} \quad (9)$$

Short-circuit current under brush:

$$I_4 = \frac{\lambda E_0 \ (1 - a_2) \ \sin \ \omega}{D} \quad (10)$$

E.m.f. of rotation of main armature circuit:

$$E_1{}^1 = jaZ \ (I_0 \sin \omega - I_4)$$

$$= jaE_0 \ \sin \omega \frac{Z_1 + Z \ (1 - \lambda)}{D}$$

E.m.f. of rotation of short-circuit under brush:

$$E_4{}^1 = jaZ \ \ (I_1 - I_0 \ \cos \ \omega)$$

$$\left. \begin{aligned} &= \frac{a \ E_0 \left\{ a Z (1 - \lambda) \sin \omega - j Z_1 \cos \omega \right\}}{D} \\ &= \frac{a_2 \ E_0 Z \sin \omega}{D} \quad \text{approx.} \end{aligned} \right\} \quad (11)$$

The power output is:

$$P = /E_1{}^1, I_1/^1 + /E_4{}^1, I_4/^1$$

$$= \frac{a \ e_0{}^2 \sin \omega}{[D]^2} \left\{ /j \left\{ Z_1 + Z \ (1 - \lambda) \right\}, (\cos \omega \ Z j \ a \sin \omega) - a\lambda \ (a \cos \omega \right.$$

$$\left. - j \sin \omega) \ /^1 + a \ (1 - a^2) \sin \omega \ / \ Z, \lambda \ /^1 \right\}$$

$$= \frac{a \ e^2{}_0 \sin \omega}{[D]^2} \left\{ /j \ (Z_1 + Z), \cos \omega - ja \sin \omega \ /^1 - \cos \omega \ /jZ\lambda, 1/^1 + \right.$$

$$a \sin \omega \ / \ Z \lambda, 1 \ /^1 - \ a^2 \cos \omega \ /jZ, \lambda /^1 + a \sin \omega /Z, \lambda /_1 + a \ \ (1 - a^2)$$

$$\left. \sin \omega /Z, \lambda \ /^1 \right\}$$

$$= \frac{a\, e_0^2 \sin \omega}{[D]^2} \Big\{ (x + x_1) \cos \omega - a\,(r + r_1) \sin \omega - \lambda_1 \,(x\,(1 + a^2)$$

$$\cos \omega = ra\,(Z - a^2) \sin \omega) - \lambda_2 (1 - a^2)(r \cos \omega - ax \sin \omega) \Big\} \quad (12)$$

As seen, in the repulsion motor, $\sin \omega$ takes the place of c, the ratio of field exciting turns to armature turns, of the series motor. $I_0 \sin \omega$ is the field exciting or magnetizing, $I_0 \cos \omega$ the compensating circuit.

At synchronism: $a = 1$, it is:

$I_4 = o$,

that is, at synchronous speed, the short-circuit current under the commutator brushes of the repulsion motor is zero, and the commutation perfect.

It is then:

$$I_0 = \frac{E_0}{Z} \frac{Z_1 + Z(1 - \lambda)}{Z_0 + Z_1 + Z \sin \omega\,(\sin \omega + j \cos \omega)\,(1 - \lambda)}$$

or approximately, neglecting Z_0, and Z_1:

$$I_0 = \frac{E_0}{Z \sin \omega (\sin \omega + j \cos \omega)} \quad (13)$$

and, absolute:

$$i_0 = \frac{e_0}{z \sin \omega} \quad (14)$$

and the power factor:

$$\left. \begin{aligned} p &= \cos\,(a + \omega - 90^\circ) \\ \text{where: } \tan a &= \frac{x}{r} \end{aligned} \right\} \quad (15)$$

The secondary current is:

$$I_1 = \frac{E_0 (\cos \omega - j \sin \omega)}{Z \sin \omega\,(\sin \omega + j \cos \omega)} \quad (16)$$

or absolute:

$$i_1 = \frac{e_0}{z \sin \omega} \quad (17)$$

hence, at synchronism the secondary current equals the primary current, and leads it by angle ω.

The power is, at synchronism, approximately:

$$P = \frac{e_0^2}{z^2 \sin^2 \omega} \Big\{ (x + x_1) \cos \omega - (r + r_1) \sin \omega \Big\} \quad (18)$$

that is, the effect of the short-circuit under the brushes disappeared.

Since the repulsion motor contains the factor $(1 - a^2)$ in the short-circuit current under the brush, I_4, which does not appear in the series motor, within the range where this factor is small,

that is, near synchronism and below synchronism, the short-circuit current is less, and the commutation, other things being equal, better in the repulsion than in the series motor. Considerably above synchronism, however, where $[1-a^2]>1$, the short-circuit current of the repulsion motor becomes large, and the commutation inferior to that of the series motor. Thus the repulsion motor is specially suited for the range of speed from standstill up to somewhat above synchronism, where the plain series motor is unsuitable by its lower power factor.

Neglecting the effect of commutation, it is:

$$I_0 = \frac{E_0}{Z} \frac{Z_0 + Z_1 + Z \sin \omega (\sin \omega + ja \cos \omega)}{Z_1 + Z} \tag{19}$$

$$I_1 = \frac{E_0 (\cos \omega + ja \sin \omega)}{Z_0 + Z_1 + Z \sin \omega (\sin \omega + ja \cos \omega)} \tag{20}$$

or approximately:

$$I_0 = \frac{E_0}{Z_0 + Z_1 + Z \sin \omega (\sin \omega + ja \cos \omega)} \tag{21}$$

$$= \frac{E_0}{r_0 + r_1 + r \sin^2\omega + a x \sin \omega \cos \omega) - j (x_0 + x_1 + x \sin^2\omega - ra \sin \omega \cos \omega)} \tag{22}$$

or, absolute:

$$i_0 = \frac{e_0}{[D]} \tag{23}$$

$$i_1 = \frac{e_0}{[D]} \sqrt{\cos^2 \omega + a^2 \sin^2 \omega} = \frac{e_0}{[D]} \sqrt{1 - (1 - a^2) \sin^2 \omega} \tag{24}$$

hence, up to synchronism: $a<1$, the secondary current is less than the primary current, at synchronism: $a=1$, both currents are equal and above synchronism: $a>1$, the secondary current is greater than the primary and does the magnetizing of the motor field.

The secondary current leads the primary current by the angle:

$$\tan \delta = a \tan \omega \tag{25}$$

The phase angle of the motor is, approximately, and neglecting the effect of commutation:

$$\tan \varphi = \frac{x_0 + x_1 + x \sin^2 \omega - ar \sin \omega \cos \omega}{r_0 + r_1 + r \sin^2\omega + a x \sin \omega \cos \omega} \tag{26}$$

The power factor is a maximum, or the angle of lag ϕ a minimum, for the brush angle ω, where:

$$\frac{d}{d\omega} (\tan \varphi) = o$$

Neglecting secondary quantities this gives:

$$\sin \omega = \frac{r(x_0+x_1)-x(r_0+r_1)}{az^2} + \sqrt{\frac{r(r_0+r_1)+x(x_0+x_1)}{z^2}+\left(\frac{r(x_0+x_1)-x(r_0+r_1)}{az^2}\right)^2} \qquad (27)$$

hence, for: $a=1$ or synchronism, if: $Z=1-10j$; $Z_0=Z_1=.1-.3j$, it is:

$\sin \omega = .235$

$\omega = 13.6$ deg.

This agrees with experimental evidence.

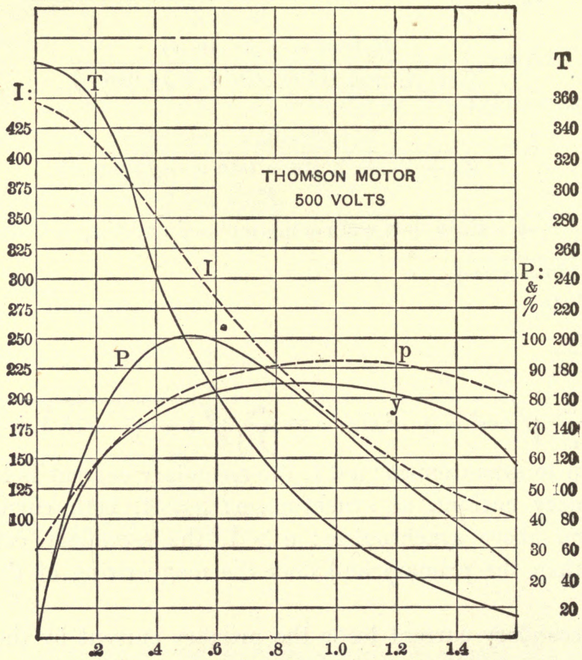


FIG. 20.

As instance are given, in Fig. 20, with the speed a as abscissæ, the characteristic curves of a repulsion motor of the constants:

$e_0 = 500$ volts,

$Z = 1 - 10j$ ohms,

$Z_0 = Z_1 = .1 - .3$ ohms,

$Z_4 = 30 - 30j$ ohms, hence: $= .18 - .15j$,

$\omega = 14$ deg., or: $\sin \omega = .25$; $\cos \omega = .97$.

Hence:

$$I_0 = 500 \frac{(1-.175a^2)+j(.007+.45a^2)}{(.335+1.89a)-j(1.07-.545a)} \text{ amps.}$$

$$T = \frac{478+13.8a-94.2a^2-24.7a^3}{(.335+1.89a)^2+(1.07-.545a)^2} \text{ synchr. kw}$$

As seen, the torque curve is extremely steep, that is, the starting torque higher than in any other motor, and torque and power become zero at a definite speed, 1.88 times synchronism. Power factor and efficiency are extremely high at low speeds, but begin to fall off beyond synchronism, though this falling off can greatly be reduced by limiting I_4.

V.

In the diagrams showing as instances the characteristic curves of different types of motors: polyphase and single-phase induction, polyphase series, single-phase series, compensated series or Eickemeyer motor, and repulsion or Thomson motor, the constants have, so far as possible, been chosen so as to represent the same motor structure: that is, to permit a direct comparison of the types, one and the same motor is assumed as operated as any of the different types, after making the changes in its electric and magnetic disposition necessary for this purpose.

In comparing the power factors it is interesting to note that the maximum power factors of the commutator motors are decidedly higher than those of the corresponding induction motors, and that, therefore, the same power factor as in the induction motor can be secured in the commutator motor with a much larger air gap between the stator and rotor. This is a very decided advantage, especially for railway work where induction motor air-gaps are mechanically extremely undesirable and unsafe.

In Figs. 21 and 22 are shown for comparison, with the speed as abscissæ, the torque and power of all the different motors. In Fig. 21 all the torque curves are reduced to equal torque at 95 per cent of synchronism. In Fig. 22 all the power curves to the same maximum output. Not too much stress, however, must be laid on these comparative curves since the characteristics of each motor may be varied to a considerable extent by the design, for instance, a motor designed for the highest possible efficiency, or highest starting torque, or best power factor, etc. Some general conclusions, however, can be drawn from these curves.

In the induction motors the torque curve is rising with the speed, in the commutator motors decreasing. The commutator motors,

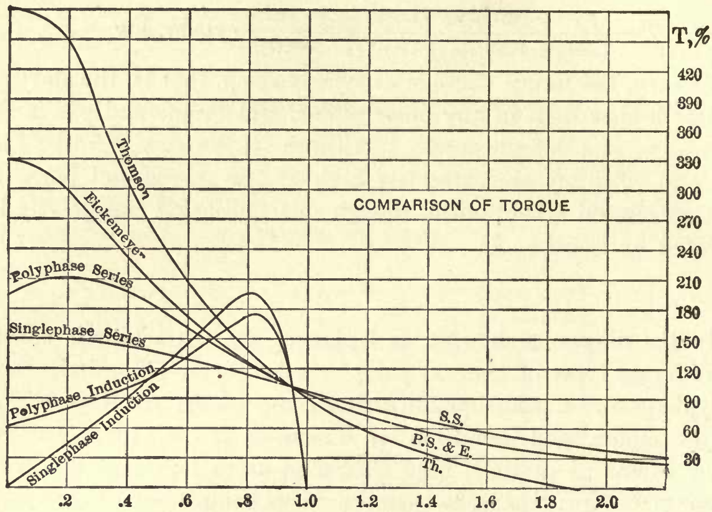


FIG. 21.

therefore, give maximum torque in starting and at low speed. The induction motors are operative efficiently only in a narrow speed

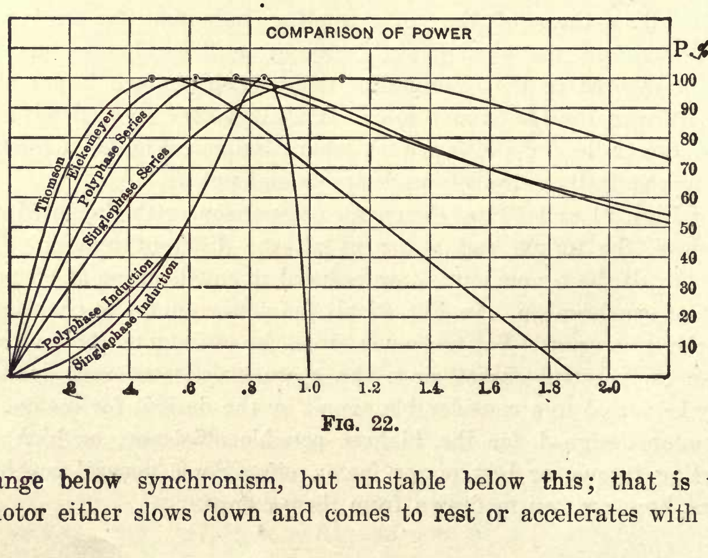


FIG. 22.

range below synchronism, but unstable below this; that is the motor either slows down and comes to rest or accelerates with in-

creasing rapidity until it approaches synchronism. At synchronism the torque and power of the induction motor reverse. High torque at low speeds can be secured only at a sacrifice of efficiency by armature resistance.

The induction motors are, therefore, essentially constant speed motors.

The repulsion motor shows the highest starting torque and the most rapid decrease of torque and power with increase of speed and reaches zero torque and power at a definite speed.

The single-phase series motor shows of all the commutator motors the lowest torque in starting, the highest at high speed; that is, its torque decreases least with increase of speed, so that in the case illustrated it almost approaches a constant torque motor.

The compensated motor is intermediate between the repulsion and series motor, but rather nearer to the former at low and to the latter at high speeds; that is, its torque is high in starting and at low speeds, but does not fall off as rapidly at high speeds as that of the repulsion motor.

To conclude, then, the induction motors are essentially constant-speed motors. The repulsion motor is a low-speed motor, the series motor a high-speed motor, while the compensated or Eickemeyer motor is intermediate between the repulsion and series motor, approaching the former at low, the latter at high speeds.

CHAIRMAN DUNCAN: **The next paper is on "Single-Phase Motors," by Mr. Max Déri, which will be abstracted by Mr. Slichter.**

SINGLE-PHASE MOTORS.

BY MAX DÉRI.

The single-phase motor has assumed of late an increasing importance since it has become known that it is not only applicable to traction, but possesses a peculiar adaptability thereto on account of the simplicity of the design, which permits of the use of high tension, and also on account of superior regulating and speed control.

It is obvious that we refer only to the single-phase motor with commutator, for the induction motor without commutator (the so-called asynchronous single-phase motor), to which we refer in this paper only for the purpose of comparison and criticism, cannot be seriously considered as a traction motor. Although views as to commutator machines for single-phase currents have become much clarified of late, and much of the prejudicial bias against them overcome, yet exact knowledge as to the internal phenomena of these machines, particularly those of commutation, is still very limited.

In this paper an attempt will be made to present a comprehensive review of the essential functions and relations of modern single-phase motors, in order to facilitate a comparison of the working conditions and commutating requirements of the different systems. The presentation of some new points of view may assist the understanding, and the many-sided and practical value of single-phase motors can be demonstrated still better by citing several hitherto unknown methods of construction.

The life of a motor system depends, above all, upon good commutation. The doubt as to the possibility of satisfactory commutation was the main cause why the value of the commutator motor and its adaptability to alternating-current did not receive appreciation. In the second place should be considered the capacity to develop sufficient torque at a moderate speed and with as high a power factor as possible. There are systems, as will be shown, which are far superior in this respect to the alternating-current series motor, and which also in comparison with the direct-current motor

leave little to be desired. Such machines, which can be designated collectively under the name "Induction motors with commutators," have two fields, one of which induces the energy current, which in connection with the other field, according to phase and space relation, produces the torque.

The generation of power currents by induction (transformation) presents the great advantage that the machines can receive high tension directly; furthermore, there follows the consequence, important in many respects, that the commutation takes place in the secondary circuit, i. e., the low-tension circuit.

The following observations are based upon the two types of series motors: First, the usual arrangement shown in Fig. 1, in which the armature with commutator and the magnetic field are connected in series across the line as in the series direct-current motor; and, secondly, the arrangement shown in Fig. 2, in which

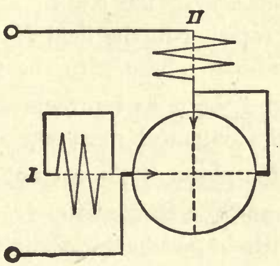


Fig. 1

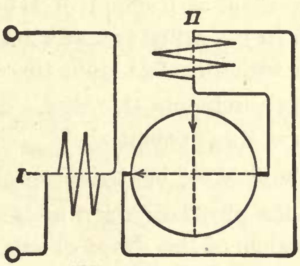


Fig. 2

the armature carrying the induced currents and the stator winding producing the field are connected in series, and short-circuited, form a closed secondary circuit.

In the first type, in which primary currents are commutated (Fig. 1), the self-induction of the armature is eliminated, for example, by a short-circuited winding on the stator, and which lies in the axis *I* of the brushes.

In Fig. 2 a transformer is combined with a motor. F_1 is the flux of the transformer, which the stator winding, *I*, constitutes with the armature, the former being connected to the main circuit. The brushes are short-circuited around the stator *II* so that the power currents in the armature produce the flux F_2. This latter field is actually the real field of the motor, because it lies in quadrature with the power currents and in conjunction with them

develops the torque. The motor is in the secondary circuit, and only secondary currents are commutated, and the potential across the brushes in the direction of the axis, I, can be established with any desired ratio of pressure reduction. (In the deductions which follow, for the sake of simplicity, the ratio is assumed as 1 to 1).

The triangle of e.m.f's. — Fig. 3 — shows the relation between the several quantities in the series motor. $\overline{ab}$ represents the line potential with respect to phase and amount or the e.m.f. (E) between the brushes induced by the field, F_1. The phase of the transformer flux, F_1, whose amount is measured by $\overline{bc}$ or $\overline{ab}$ respectively, lies at right angles to these vectors, and for the primary series motor in the direction $\overline{ad}$, and for the secondary series motor in the direction $\overline{ad_2}$.

In both cases F_2 is excited by the armature current (power current I), F_2 and I are, therefore, always in phase. At any speed n, expressed as a fraction of synchronous speed, the e.m.f., E_a, induced in the armature, as a result of rotation in the field F_2, is in phase with this flux and, therefore, also in phase with the power current producing this flux. This e.m.f. $\overline{bc}$ is so represented that the exciting potential E_m, i. e., the potential necessary to excite the flux F_2, is at right angles to the phase of the current $\overline{ac}$.

In the phase direction $\overline{bc}$ is also found the ohmic drop Ir. The magnitude of this drop, which is of little importance in the relation and phase of the working quantities, as also the potential in the direction $\overline{bc}$ which is necessary to excite the stray field, will be left out of consideration in order not to render difficult the consideration of the general questions. These omitted quantities can be considered later, in the well-known way, in calculating the efficiency, temperature rise, etc., etc.

The triangle $\overline{abc}$ is the diagram of the series motor, and with its aid all the quantities involved can be deduced. In this diagram the phase angle δ assumes particular importance, not only for the determination of the power factor, but also to indicate the relation between the various quantities involved.

$$F_1 : \frac{1}{Z}\,\overline{bc}, \text{ or}: \frac{1}{Z}\,\overline{ab}; F_2 : \frac{1}{Z}\,\overline{ac}; I: \frac{\rho}{Z_2^2}\,ac$$

The sign : is that of proportionality; Z_1 and Z_2 the respective number of turns, although not variable, are given in order to indi-

cate the dependence of the flux upon them. The same is true of the magnetic resistance ρ, which is only slightly variable between practical limits. The length $\overline{ac}$ is, therefore, the measure of both the flux F_2 and approximately also of the current I, the phase directions of both falling in $\overline{bc}$.

The torque $T: \frac{\rho Z_1}{Z_2^3} \overline{a c}^2$

The speed $n: \left(\frac{Z_2}{Z_1}\right) \frac{\overline{bc}}{\overline{a c}}$

The actual power output of the motor $P: \left(\frac{\rho}{Z_2^2}\right) \overline{a c} \times \overline{b c}$

The internal power factor $\cos \delta : \overline{bc}$.

Making $\overline{ab} = E$ and expressing above quantities as functions of the angle δ,

$I : E \sin \delta$; $T : E^2 \sin^2 \delta$; $P : E^2 \sin \delta \cos \delta$, and $n : \operatorname{cotg} \delta$.

The apparent power output $E \times I : E^2 \sin \delta$.

If we project $\overline{c}$ on $\overline{ab}$, according to the above for $E = ab = 1$, $P : \overline{cg}$; $E \times I : \overline{ac}$; $T : \overline{ag}$.

In Fig. 4 the quantities T, P and $\cos \delta$ are constructed as functions of the speed, as $n : \cot \delta$, referred to a constant $\sin \delta$, is used as the axis of abscissæ. It appears clearly, from these curves, how rapidly T diminishes with increasing speed. In the case of the primary motor $\delta = \varphi$. In the case of the secondary series motor, it is necessary also to know the phase of the primary current. For this purpose we proceed according to Fig. 5 as follows:

The magnetizing current of the field F, in relation to the number of effective armature turns Z_1 is $i : \frac{\rho}{Z_1^2} \overline{ab}$, its phase is at right angles to $\overline{ab}$. If we lay down this constant value, in the ratio $\frac{\overline{bc}}{\overline{ac}}$ then $\overline{cc^1}$ becomes the component of pressure by which the phase of the primary current $\overline{bc^1}$ is determined. The difference in phase between the primary and secondary currents is φ_1, and $\cos \varphi = \cos .(\delta + \varphi_1)$ is the external power factor of the system.

The magnitude of $\overline{cc^1}$ is proportional to $\cot \delta$ and consequently to n. Similarly as in Fig. 4, referring to $\sin \delta$ as constant, we obtain the geometric locus of the points c^1 as a curve which at first gradually diverges from the circular arc in going from b toward a, then rapidly diverges and finally becomes assymptotic

to $\overline{ad}$. The point of counter curvature of this curve corresponds to the values of δ and n at which $\cos \varphi$ is a maximum.

In the secondary series motor $\cos \varphi = 1$ cannot be reached; $\cos \varphi$ in the case of primary and $\cos \delta$ in the case of the secondary motor can only approach the value unity in the case of an ideal no-load operation.

As regards the process of commutation, we shall investigate in addition to the so-called reactance voltage, also the e.m.f's. in-

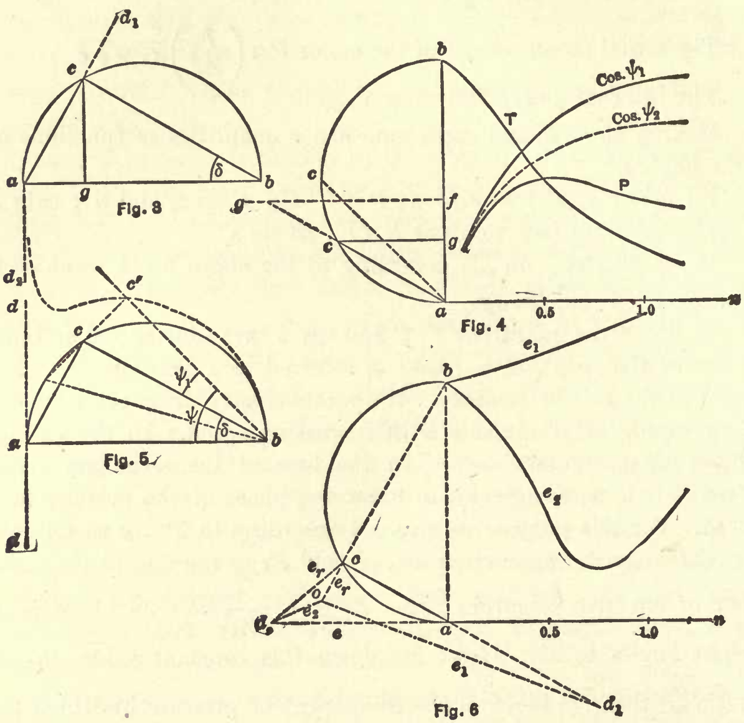


Fig. 3
Fig. 4
Fig. 5
Fig. 6

duced in the short-circuited turns by the fluxes F_1 and F_2. These e.m.f's. are usually of a higher order, quantitatively, than the reactance voltage produced by the variation of contact between brush and commutator for the latter, as in the case of direct-current machines, is determined only by the stray field which is interlinked with the short-circuited turns, while the former are due to the total flux. The coil, short-circuited during commutation, is interlinked with the flux F_2 and at the same time cuts the field

flux F_1 in its densest zone with a speed corresponding to n. There are, therefore, induced in the coil two different e.m.f's. both of the same frequency: i. e., $e_1 : F_2$ independent of the speed, proportional to F_2, with the phase of which it is in quadrature; and the $e_c : nF_1$, proportional to the speed and to F_1 and in phase with F_1.

The diagram of these e.m.f's. can be derived directly from the e.m.f. triangle Fig. 3, as shown in Fig. 6.

Let $\overline{ab}$ represent the measure of the e.m.f. e_1 corresponding to F_2 maximum and for a certain speed n : cotg δ. Draw the triangle $\overline{abc}$. The phase direction of F_2 is $\overline{bc}$, e_1 is at right angles to it and proportional to F_2 and hence determined by $\overline{ac}$ in dimension and phase. The magnitude of e_0 in the direction of F_1, is $\overline{ad}$, at the speed n for instance.

For the primary series motor $\overline{ad_1}$: $\dfrac{\overline{bc}^2}{ac}$ for the secondary $\overline{ad_2} = \dfrac{\overline{bc}}{ac}$. The resultant e_0 of the e.m.f's. is cd_1 or cd_2 respectively.

As far as the reactance voltage e_r is concerned, its phase coincides with the current phase, being in the direction $\overline{bc}$, and quantitatively $_r : nI : E_a$ (on a scale approximately 0.1 — 0.2 $\overline{bc}$). From the diagram it appears that in the case of the primary motor, e_r and e_0 are always at right angles to each other, whereas in the case of the secondary motor the obtuse phase angle is variable and only at practicable speeds e_r and e_0 are opposed to one another. In the case of the secondary commutation we, therefore, arrive at an advantageous compensation of the reactance. The result of all three e.m.f's. in the short-circuited winding, e measured by $\overline{od_1}$ or $\overline{od_2}$ respectively must be considered in the commutation as the cause of sparking.

In Fig. 6 curves of e are shown for both methods of connecting the series motor. One sees that e in the case of the primary series motor (e_1) deviates but little from its initial value, and increases at greater speeds. In the case of the secondary series motor, on the contrary e_2 falls considerably below its initial value and is a minimum at a speed which lies within the limits of the usual operating speeds. The latter, therefore, commutates considerably better than the primary motor in which good commutation is out of the question.

We shall investigate in a similar way the repulsion motor in

Fig. 7. The stator winding is connected to the line and the brushes, inclined to the axis Y at an angle α, are short-circuited. The brush axis is indicated as X. We shall not proceed with the investigation of the operation of this motor according to the method usually followed of resolving the fields, e.m.f's. and ampere-turns into components as functions of sine and cosine α, but we shall proceed in other ways which are simpler and unobjectionable.

We may proceed in two ways: According to Fig. 8, we can divide the stator winding, which we may assume as uniformly distributed over the circumference of a closed stator, into two groups connected in series with the same current flowing through them and which exert and are subjected to the same effect as the combined system. The four groups of windings on the stator, as shown

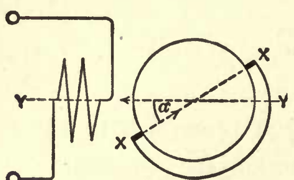


Fig. 7

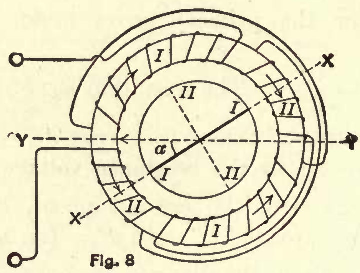


Fig. 8

in the figure, are so connected as to produce, by the current flowing in all of them, the flux in the direction of the arrow, and to generate the field with the axis Y. In the distribution of the lines of force and the amount of magnetizing current, there must be taken into account, in addition to the magnetic resistance of the entire flux, the reaction of that part of the armature circuit which is short-circuited between the brushes. None of the effects suffer any change if we consider, as connected in the order shown, the ampere-turns I whose axis coincides with X, and the ampere-turns II, whose axis is perpendicular to X. Only the sequence of the single elements in the series has been changed, which is without any importance on the result. We have, therefore, two stator windings I and II, in general with different number of turns and also of different magnetic resistance, and the arc covered by the windings and the polar arc are unequal. The axis of the two windings are perpendicular to each other. We can, therefore, construct the diagram Fig. 9.

We can proceed in another way in accordance with Fig. 10. In accordance therewith, the armature winding is divided into four groups which are connected in pairs *I* and *I*, then *II* and *II* in parallel, and the two pairs connected in series are closed on

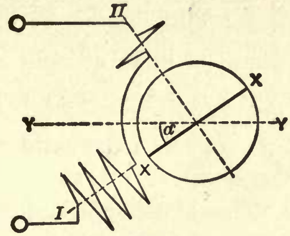


Fig. 9

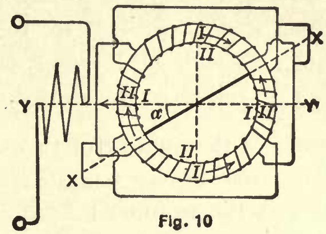


Fig. 10

themselves. The division is such that the groups connected together when traversed by the current produce the same magnetic field in the direction of the arrows and corresponding with the brush axis *X*, as would the entire armature winding when short-circuited through the brushes. It appears, therefore, that the armature phenomena are as follows: In winding *I* an e.m.f is

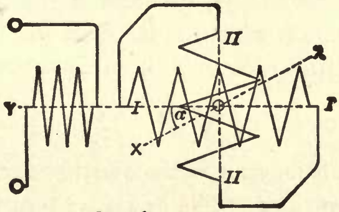


Fig. 11

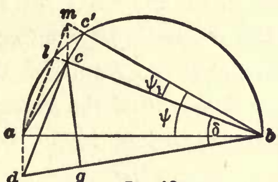


Fig. 12

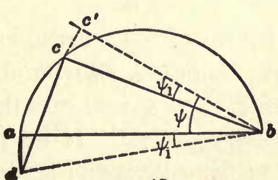


Fig. 13

induced by the coaxial stator winding, which e.m.f. is equal to that of the entire armature; winding *I* forms a circuit closed through winding *II*, hence excites a flux in the latter which is free from any armature reaction. The diagram of this arrangement, in accordance with the foregoing analysis, is shown in Fig. 11.

This diagram differs from the arrangement shown in Fig. 2 in that the winding exciting the field is not on the stator but on the

rotor. Whether the armature rotates in a field excited by fixed stator windings or by rotor windings amounts to the same inducing effect, provided only that in the latter case the axis of the exciting windings is held fixed by brushes.

According to the first arrangement the coils I are the inducing winding, and according to the second they are the induced winding; the coils II, however, on account of being at right angles to X or Y, respectively, can neither exert nor receive any induction. The ratio of the number of turns $\frac{Z_1}{Z_2}$ is $\frac{90^\circ - a}{a}$; the ratio of the poles faces the reciprocal $\frac{a_1}{90_0 - a}$. This alone sufficiently indicates the importance of the brush position, represented by the angle a and its effect on the flux, torque, etc. It appears also that by a variation of this angle by turning the brushes, all of the secondary quantities and their functions can be varied.

In Fig. 12 the armature current I in amount and phase is determined graphically by the following considerations:

$\overline{abc'}$ is the diagram of the primary pressures, $\overline{ab}$ the terminal pressure, $\overline{bc}'$ the e.m.f. of the armature and also the pressure of the stator winding I, and ac^1 that of the stator winding II. F_1 is proportional to $\overline{bc'}$ and in the direction $\overline{ac}^1$; the same is true of i. The component of the armature e.m.f. which, induced by the components F_2, belonging to the exciting current, i, is proportional to F_2 and to n: $\frac{\overline{bc'}^2}{ac}$ and can be measured by $\overline{cc}'$. Then $\overline{bc}$ is the component of the armature e.m.f. belonging to the exciting current I and, therefore, also the direction of I. The angle φ_1 lying between $\overline{bc}'$ and $\overline{bc}$ indicates the phase difference between primary and secondary current. If we prolong $\overline{bc}$ until it cuts the circle in l and we draw through l the line $\overline{am}$ until it cuts $\overline{bc'}$ prolonged, then, owing to the equality of the angles, $\overline{am} = \left(\frac{bc}{bc'}\right) ac'$; $\overline{am}$ is, therefore, the measure of I, which is parallel and equal to $\overline{cd}$, produces the right-angled triangle $\overline{bcd}$ similar to $\overline{bc'a}$. The first is the diagram of the e.m.f's corresponding to the current I. The connection $\overline{ad}$ can be proven to be always perpendicular to $\overline{ab}$, and, $ad : n \left(\frac{Z_2}{Z_1}\right) \overline{ab} \,.\, \overline{bc}$ and $\overline{cd}$ are the quantities which are a

measure of the torque and capacity because they depend on the armature current and on the component of the field which is in same phase with it.

We are obviously led to the same result if in investigation of the repulsion motor we proceed according to Figs. 10 and 11. The following consideration is much simpler than the foregoing and leads directly to the diagram of Fig. 13.

This is also the proof and confirmation of the result of the previous deductions. In this case the internal circuit consists of the two rotor windings I and II. In winding I the e.m.f $E:\overline{ab}$ is induced by a constant F_1. On rotating the armature the winding I cuts the flux *II,* and winding *II* the flux *I.* The e.m.f's. induced as a result of the rotation have the phase direction of the inducing fields. $E_a . \overline{bc}$ is of the same phase as *I;* the e.m.f. in winding *II* E_k is at right angles to $\overline{ab}$.

$$E_k : \overline{ad} : nZ_2 F : n \left(\frac{Z_2}{Z_1}\right) \overline{ab}.$$

The polygon of e.m.f's. is $\overline{abcda}$ in which $\overline{ad}$ is a compensating e.m.f. proportional to the speed, adding itself geometrically to the line pressure.

We can indicate the important quantities by Fig. 14, by con-

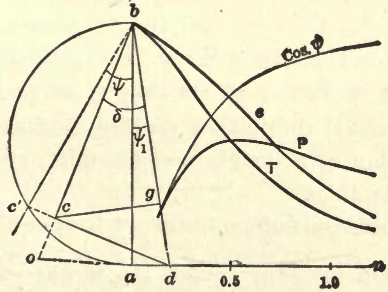


Fig. 14.

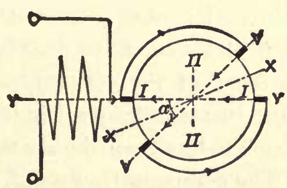


Fig. 15

structing $\overline{ad} : n$ perpendicular to $\overline{ab}$, drawing the semi-circle around $\overline{bd}$, and determining the point $\overline{c}$ according to n : cot δ. The quantities $\overline{bc, cd}$ and also $\overline{cd}$ and $\overline{dg}$ will vary in the ratio

$$1:\sqrt{1 + n_2 \left(\frac{Z_2}{Z_1}\right)^2}$$ *T* and *P* will also increase with corresponding coefficients. The output of the repulsion motor will be as great as corresponds to the line pressure, and consequently at a given

speed as great as in the case of the primary and greater than in the case of the secondary series motor.

Since the compensating e.m.f. furnishes a part of the field excitation, it is necessary to provide a less number of ampere-turns externally in the ratio $\frac{ac}{cd}$ as shown in Fig. 14. It can be shown that $\overline{ac} = \overline{bd} \sin(\delta - \varphi_1)$ while $\overline{cd} = bd \sin \delta$. For small values of δ in which $\overline{cd}$ still has a considerable value. $\overline{ac}$ may become small.

In addition, the compensating effect of $\overline{ad}$ is manifested by the fact that the phase difference between the power current and the e.m.f. is diminished by the angle φ_1. The phase shifting which takes place in the transformer I is to a certain extent balanced by the compensation. Cos φ will be about the same as in the case of the primary series motor and will, therefore, approach closer to the maximum value than in the case of the secondary series motor.

The commutation phenomena in the case of the repulsion motor can be represented by consideration similar to the foregoing, taking into account, however, that the e.m.f's. e_1 and e_c are induced by those fluxes, which, according to the analysis of Fig. 9, correspond to the number of turns Z_1 and Z_2. Therefore Fig. 14 shows also on the proper scale the diagram of e.m.f's. in the short-circuited winding. In amount and phase direction e_1: $\overline{cd}$, e_c : ad and e_0: $\overline{ac}$; $\overline{ao}$ is, therefore, the e.m.f., e, resultant of all three. $\overline{ad}$ is proportional to the speed. We can, therefore, project the values of c as ordinates upon n. The curve shows the dependence of e upon n. e is, therefore, a maximum at starting (just as in the case of the series motor $e : \overline{ab}$), diminishes rapidly, however, with increasing speed and reaches at a certain speed a minimum, which is less than the reactance voltage.

The compensating e.m.f. of the repulsion motor depends upon the ratio $\frac{Z_2}{Z_1}$, hence upon $\frac{a}{90^\circ - a}$. On the other hand, the torque and energy of this motor is inversely proportional to the number of turns, i. e., inversely proportional to Z_2 or to higher powers of Z_2. Herein lies the weakness of the ordinary repulsion motor. It is not at all sufficient, as was originally believed, to shift the brushes by 45 deg. (i. e., one quarter of the polar distance), which would correspond to the ratio $\frac{Z_2}{Z_1} = 1$. The e.m.f. induced while at rest

in the winding I would be barely sufficient to excite the field $F'_2 = F_1$ with the current $I = i$. The maximum power current would be i, hence the starting power too small and the output insufficient. Consequently it is necessary to make the angle a much less than 45 deg. in order to obtain sufficient torque. In reality the angle is chosen at about 25 deg. to 20 deg., corresponding to a value $\frac{Z_2}{Z_1} = 0.40$ to 0.30. In order, therefore, to obtain a greater output one sacrifices a part of the compensating effect.

The repulsion motor is, nevertheless, a very useful machine, particularly if the windings are carried out in two parts, as shown in the diagram, Fig. 9. With the aid of a switching arrangement, reversal of direction and control is easily made by the inversion and variation of the field of force. Another and more convenient method for the reversal and control within the widest limits consists in varying the ratio $\frac{Z_2}{Z_1}$ by shifting the brushes. In order to obtain the maximum output, it would be necessary to make a so small that it would embrace only two to three commutator bars, which would, however, make the motor unreliable in operation and commutation. On this account the output of the repulsion motor is limited; in other words, dependent upon the number of the commutator bars and the size of the commutator.

We will now refer to an arrangement devised by the author according to Fig. 15, in which all of the characteristics of the repulsion motor are left substantially undisturbed, permitting, however, the angle a to be made twice as large as with the usual arrangement. One pair of brushes is placed in the Y axis and another pair at the angle in the V axis. The two pairs of brushes are connected as shown, so that they embrace the obtuse angle $(180 - a)$. The effect of this arrangement can be judged if one imagines an armature in the Y axis connected, as shown in series and in closed circuit with another armature in the V axis. The ratio of the number of turns $\frac{Z_2}{Z_1}$ in accordance with the diagrammatic analysis is in this case $\frac{a_1}{180° - a_1}$. If this ratio and the resulting output are to be of the same value as before, i. e., $= \frac{a}{90° - a}$, then will $a_1 = 2a$.

The brushes have to carry the same load in this arrangement as

in the case of the ordinary repulsion motor with the same power current and cross-section of all brushes. The number of brushes need not be increased if with the proper winding of the armature fewer brushes are used than the number of poles, for instance, for eight poles, two positive and two negative poles have two brushes each.

This arrangement is particularly adapted to controlling by brush shifting, perhaps by shifting the V brushes alone. According to the above presentation a compensating effect is obtained either by exciting the field by primary current, one component of which is the magnetizing current for the flux F_1, or by placing the windings which excite the field and which are a part of the main circuit on the armature and subjecting them to induction by F_1.

Both of these causes of the compensating effect are contained in the arrangement of Fig. 16, which shows the so-called compen-

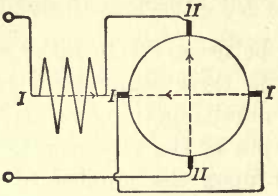


Fig. 16

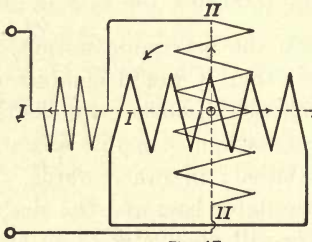


Fig. 17

sated motor of the Union Elektrizitäts-Gesellschaft. The brushes in the axis I are short-circuited. The diagonal brushes in this axis II are traversed, on account of the series connection with the stator, by the main current, either directly or at a transformed potential through the insertion of a transformer. The armature carries the power current in short-circuit and rotates in the field of force excited by the primary current in the armature between the diagonal brushes.

The actions in the two axes of the armature do not interfere with one another notwithstanding that they occur in a common winding, because the axes lines are in neutral positions relatively to each other. Considering that the axes are held fast in the armature by the brushes, the arrangement can also be represented by the diagram of Fig. 17.

The diagram of the working current is similar to that of the repulsion motor.

Fig. 18 shows the polygon of e.m.f's. $\overline{abcda}$ with relation to the working current. The e.m.f. of the armature coil *I,* which is reflected in the stator winding, is made up of $E_a : \overline{bc''}$ and $E_0 : \overline{ak}$. These e.m.f's. are generated by the rotation of the coil in the two components of the field F_2, one of which is excited by *I,* the other by *i.* The e.m.f., $E_n : \overline{kd}$, is induced in the armature coil *II* on account of its rotation in the field F_1; on the other hand, $E_m : ac''$ is consumed in exciting the field of force and the stray field. E_0 and E_n have the direction $\overline{ad}$; $\overline{ab}$ and $\overline{bd}$ form the angle γ.

In order to construct the diagram, with relation to the working current, $\overline{ad}$ is drawn at right angles to $\overline{ab}$ $\left(ad : \tan\ \gamma : n \left(\frac{Z_2}{Z_1}\right) \overline{ab}\right)$. On bd as the total useful e.m.f., the work polygon is constructed for $n : \cot\ \delta$, in which all quantities $\overline{ad}$, $\overline{bc}$ and $\overline{cd}$ are referred to

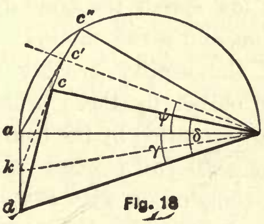


Fig. 18

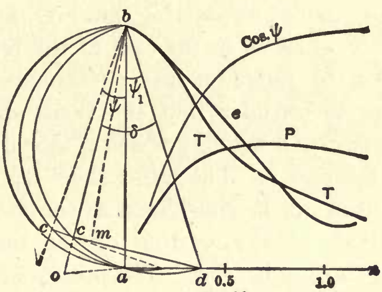


Fig. 19

the phase and amount of the working current *I.* Not only is the phase displacement and the drop in voltage caused by the transformation, compensated for in this way, but the primary diagram also receives a favorable displacement.

On the assumption of the direct connection in series between the stator winding and exciting winding, $\overline{ak}$ and $\overline{kd}$ are equal in amount, $ad : \tan\ \gamma$ is, therefore, twice as large, and the compensating effect more powerful in the same proportion than in the repulsion motor. $\overline{bc'}$ shows the direction of the primary current; ac' is the measure of the exciting e.m.f. to be supplied externally.

By the insertion of the series transformer the compensation can be varied together with the ratio $\frac{Z_2}{Z_1}$ Still greater is the variation if

with the aid of a potential regulator the number of turns in both be varied simultaneously in opposite directions.

The example in Fig. 19 shows the stronger influence of $\overline{ad}$ upon $\cos \delta$, T and P. One can see that $\cos \varphi$ approaches the value of unity more rapidly than in the case of the repulsion motor, and becomes unity at a practicable speed.

The exciting voltage $\overline{ac^1}$ which is supplied externally diminishes rapidly in this arrangement and can reach zero, in which case the field excitation is accomplished by the compensating e.m.f. alone.

As for the commutation, it is necessary to judge the performance of the brushes in the axis I carrying the working current, in a way similar to that of the repulsion motor, but the fundamentally different phenomena which takes place in connection with the exciter brushes must be investigated from a special point of view. Fig. 19, which shows the e curve for the brushes carrying the working current indicates that the commutation at normal speed is favorable; on starting, however, and at low speeds the same difficulties exist as in the case of the repulsion and series motors. In order to judge of the performance of the exciter brushes, we have to consider that the turns short-circuited by these brushes are part of a winding which is already short-circuited by the brushes in the axis I. The latter short-circuiting with full contact of the brushes can be considered as constant in comparison with the very variable short-circuiting of the individual turns by the leading and trailing brushes. The pressure diagram of the armature ($bcmb$ in Fig. 18) is composed of the e.m.f's. induced by F^1 and generated as a result of the rotation in the entire field of force, and also of the small $\overline{cm}$ which represents the exciting e.m.f. for the stray field in the armature. The same relations hold also for the e.m.f's. in the commutating coil, which are induced under similar conditions as the whole armature winding in the axis I. Only the scale of the vectors is different in the ratio of the number of turns and the local distribution of the field of force (about in the ratio $\frac{\pi}{2} \frac{Z_0}{Z_1}$).

During the period of commutation the e.m.f., $\overline{cm}$, exciting the stray field, and, therefore, the exciting current, will vary but little. In addition there will appear a small reactance pressure. The latter is unimportant in the production of sparking, because the exciting current, which varies with the contact of the brushes II,

which as a rule is weaker than the working current, finds an equalizing shunt circuit in the short-circuited connection of the brushes *I.* The influence of the residual e.m.f., *e,* on the commutation is doubtless small. The commutation under the exciting brushes proceeds without difficulty and requires no special care or consideration.

The so-called compensated single-phase motor represents on the whole an improved repulsion motor. In comparison it shows, however, some disadvantages, because in addition to the double system of brushes, a special transformer for excitation and special arrangements for regulation are necessary.

If we wish to investigate in the same manner the ordinary single-phase induction motor having a squirrel cage armature and no commutator, we recognize an analogy with the previously described arrangements which becomes more complete when we consider both pairs of brushes as separated from the stator circuit, and each pair as short-circuited on itself, as indicated in diagram, Fig. 20.

In order to proceed from this arrangement to the induction motor, it is only necessary to imagine instead of the armature short-circuited by the brushes in two diagonal directions, two diagonally-placed short-circuited coils, or as a further simplification a single short-circuited coil effective in both directions.

The diagram of e.m.f's. is shown in Fig. 21. In the axis *I,* the e.m.f. $\overline{ab}$ is produced by the line voltage or F_1. There will be induced an e.m.f. $\overline{ac}$ in the axis *II* in proportion to the speed and in phase with the generating flux *I,* hence at right angles to $\overline{ab}$. The currents corresponding thereto excite a cross-flux which penetrates through the rotor and stator. These magnetizing currents as well as the cross-flux F_2 excited by them have the direction $\overline{ad}$.

The direction $\overline{ad}$ diverges but little from $\overline{ab}$ (in contradistinction to the previous treatment, this acute angle cannot be neglected, nor can the ohmic drop, because both are important working factors of this motor). Having the same phase direction, there is generated in the axis *I* of the armature winding at a certain speed, an e.m.f. $\overline{ae}$ in phase with F_2 and proportional to n^2. Out of the resultant e.m.f. $\overline{ae}$, there appear the ohmic drop $\overline{bf}$ and at right angles thereto the e.m.f. $\overline{ef}$ exciting the stray field in the armature. $I: \overline{ef}$ the phase of the working current is $\overline{bf}$ $F_2: n\ \overline{ab}$, the phase of the field $\overline{ae}$. The angle β between the direction of these two phases, whose cosine is a measure of *T,* will be disadvantage-

ously large with the exception of small values of $\overline{ef}$ near to synchronism. The same is true in reference to φ, which is greater by $(\varphi_1+\gamma)$ than the angle previously referred to. The power factor will be poor between rest and a speed slightly under synchronism. The motor can, therefore, operate advantageously only at nearly synchronous speed, but even then only with limited output, because at this speed a small e.m.f. $\overline{be}$ remains, and the working current is, therefore, weak. The triangle $a^1\ bc^1$ shows the work diagram of the induction motor and contains the quantities T, P and $\cos\ \delta$.

These considerations confirm the well-known fact that the induction motor without commutator for single-phase current is an undesirable machine — quite independent of the fact that it has no

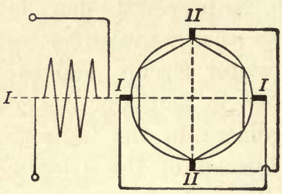


Fig. 20

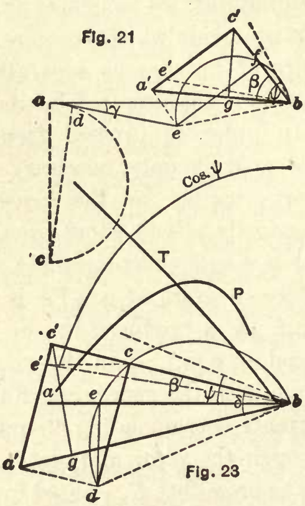


Fig. 21

Fig. 23

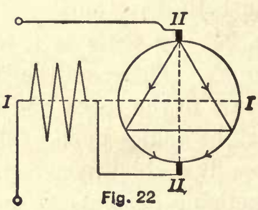


Fig. 22

starting torque, so as to start itself, and because it admits of no external control on account of its being exclusively self-exciting.

As an appendix to these considerations the author submits his arrangement which shows the application of the commutator and the externally excited field in combination with the closed circuit armature.

Fig. 22 is the diagrammatic representation of this motor and Fig. 23 the vector diagram.

The armature winding is closed for the smallest possible number of phases, which must be different from the number of poles. The

commutator carries the exciter brushes at right angles to *I* in the axis *II*. The brushes are connected directly or by means of a transformer in series with the stator winding. The working currents are induced by F_1 in the short-circuited armature without brushes. In spite of the short-circuiting the excitation of F_2 in the armature winding can take place as the exciting currents flow partly through turns of the armature and partly through short-circuiting connections, as indicated in the diagram by the arrows and as represented in Fig. 24 more clearly in the case of a four-

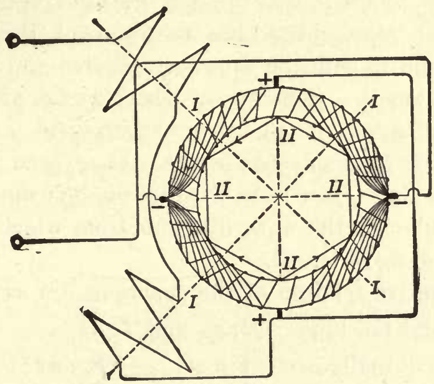


Fig. 24

pole armature having a six-phase short. The field flux is developed of variable density in different parts of the pole faces but with definite polarity. The field excited by a part of the armature winding and held fixed by the brushes attracts the short-circuit currents whereby the armature is set in motion. With increasing speed there appears not only the compensating e.m.f. previously referred to but moreover an exciting e.m.f. which has its seat in the closed circuit winding. The machine constitutes to a certain extent an externally excited and consequently externally controllable induction motor.

The e.m.f. polygon is according to Fig. 23 $\overline{abcdea}$. $\overline{ae}$ is the e.m.f. induced by rotation in the self-excited field, $\overline{bc}$ the e.m.f. induced by rotation in the externally excited field F_2 in phase with *J*, and $\overline{de}$ that induced by rotation in *F*, as well as in the component of F_2 in phase therewith and $\overline{cd}$ the exciting e.m.f. consumed in the main circuit. Under these conditions we have neg-

lected the angle γ which characterizes the phase of the self-excitation, as in the analogous diagrams of the other commutator motors.

In this case also appears the compensating effect of e.m.f. $\overline{de}$, to improve the power factor as well as the power output. This e.m.f. has, moreover, a favorable effect on the operations which take place in the short-circuit of the induction motor, as the phase direction of the working current $\overline{bc}$ is brought near to the direction of $\overline{ce^1}$ which is the direction of the cross-flux, self-excited in the short-circuit armature, and which direction departs but slightly from $\overline{ab}$. The angle β between the working current — and the total flux ($\overline{be^1}$ representing the resultant of the e.m.f. values, which correspond to both the externally-excited and the self-excited flux) will be small. Consequently both parts of the combined motor, even at speeds much below synchronism, are found to be operating under favorable conditions. Cos φ can be made equal to unity or nearly so, just as in the case of the compensated motor. The triangle a^1bc^1 is the work diagram from which the quantities T, P and cos δ are obtained.

The quantitative relation of the functions are as follows:

1. In the total machine: $E:\overline{ab}$ and $I:\overline{de}$;

2. In the externally-excited machine: $E_a:nI:\overline{bc}$, $E_k:n^2I:\overline{de}$;

3. In the self-excited machine i. e., in the induction motor, $E_1:n^3I:\overline{ae}$. The total flux F_2 is composed of the externally excited component $(:J)$ and the self-excited component $(:\frac{E_1}{n}:n^2I)$; and at ordinary speeds is nearly equal to the sum of these values. The exciting e.m.f. necessary to expend $E_m:\overline{ce}:\overline{bd}\sin(\varphi - \varphi_1)$, which is measured between the exciter brushes is practically small and can also become zero. $T:(1+n^2)I^2$; $P:n(i+n^2)I^2$ and

$$I:\frac{E}{n^3+\sqrt{1+n^2-n^4}}$$

This kind of motor is far superior to all the commutator motors previously described as regards commutation. Brushes carrying main working currents are not used; therefore, all commutator difficulties at starting and at low speeds disappear entirely. For this reason the motor becomes nearly independent of the armature current. Therefore, from this standpoint machines can be built in units of any desired size quite the same as with polyphase motors. The commutation at the exciting brushes is, as previously shown,

very smooth, particularly in this case, because the turns in closed circuit under the brushes are really parts of closed circuits and because the currents which flow through the brushes have only to furnish a small part of the excitation; they need, therefore, be comparatively small for this reason and especially because the brush e.m.f. $\overline{ce}$ will be very small at normal speeds.

The commutator for this reason can be made much narrower, an advantage which is important in connection with the fitting into car bodies; of equal advantage is the possibility of using a comparatively small number of brushes. In principle, this motor is an induction motor which transmits external energy by means of transformation to a simple rotor; the torque and speed can nevertheless vary, and any variation can be produced which is necessary for the control of vehicles or cars. The motor can be started with considerable torque, and its power factor can be made nearly unity. By this combination we have an externally excited, compensated induction motor.

ALTERNATING-CURRENT MACHINES WITH GRAMME COMMUTATORS.

BY MARIUS LATOUR, *Delegate of Société Internationale des Électriciens.*

If we refer to the technical literature of four or five years ago we shall notice that the problems, the solution of which was sought by engineers applying themselves to the study of alternating-current machinery, were:

1). The development of alternators in which all difficulties in parallel running should be done away with.

2). The construction of generators of constant voltage.

3). The construction of motors working with a good efficiency at all speeds, and starting under load with single-phase current.

4). The construction of non-synchronous motors working with a power factor equal to unity.

It was about that time that I began to take an interest in the application of the Gramme commutator to alternating-current machines. I have thus been led to a new system of electrical machinery which might take the place, either as generators or motors, of the machines used nowadays and solve, from the technical point of view, all the problems set forth.

The description of alternating-current machines comprising a Gramme commutator is comparatively old. Indeed, it is to be traced back to Messrs. Elihu Thomson, Wightman, and Wilson. However, owing partly to the essential phenomena exhibited in direct-current armatures traversed by alternating currents not being very well known, partly to the little interest taken by electricians in these phenomena, partly to the bad opinion that had been formed of the Gramme commutator used in connection with alternating currents, the arrangements proposed by those inventors were left without much industrial value.

I soon realized that the use of the Gramme commutator with alternating currents was full of capabilities and I have been able to realize the machines concerning which I shall say a few words.

All these machines have a uniform appearance, due to their comprising a stator with a winding distributed in slots, and a rotor

similar to a direct-current armature with a commutator. These machines are:

1). The panchronous self-exciting polyphase generator.

2). The panchronous self-exciting single-phase generator.

3). The polyphase motor at variable speed with a power factor equal to unity.

4). The compensated single-phase motor.

5). The repulsion motor.

6). The single-phase series motor with perfect commutation.

1. *The Self-Exciting Polyphase Generator.*

This generator is represented in its two most interesting shapes by Figs. 1 and 2, the former showing the shunt connection, and the latter the compound connection. S is the stator, R the rotor with commutator, and t the transformer for supplying the rotor. Such generators are connected to a network like direct-current generators, without any synchronizing operation. The compounded alternator, when well regulated, works at constant voltage whatever may be the inductive or non-inductive load on each phase separately.

2. *The Self-Exciting Single-Phase Generator.*

This generator is represented in its two most interesting shapes by Figs. 1_1 and 2_1. In order to allow self-excitation two sets of brushes c d are short-circuited on one another. In reality, for the sake of commutation, it is preferable to have several sets of brushes short-circuited on one another, as represented by Fig. 3. The self-exciting single-phase generator has, above the ordinary generator, besides the two advantages regarding the easier parallel running and the perfect compounding, that of admitting a perfect rotary field without any harmonic field likely to weaken the efficiency.

3. *The Polyphase Motor at Variable Speed with a Power Factor Equal to Unity.*

This motor corresponds to Fig. 1 (representing the shunt connection of the panchronous generator), the transformation ratio of the transformer t being supposed to be arbitrary and variable. The speed of the motor may be regulated by changing the transformation ratio of the transformer. The power put into play in the transformer is the larger, the greater the slip of the motor. Such a motor may work with a power factor equal to unity at normal speed.

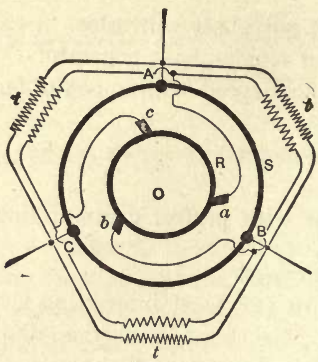


Fig. 1

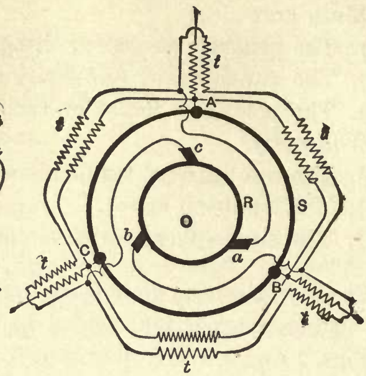


Fig. 2

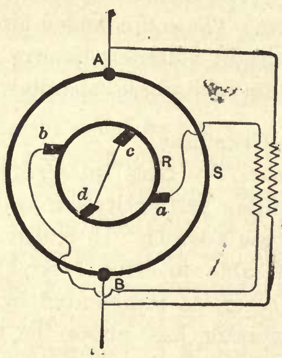


Fig. 1_1

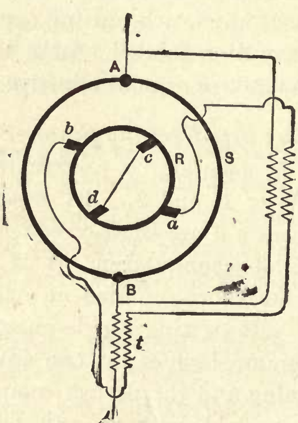


Fig. 2_1

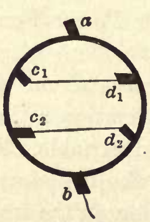


Fig. 3

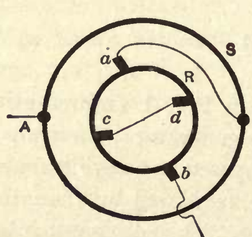


Fig. 4

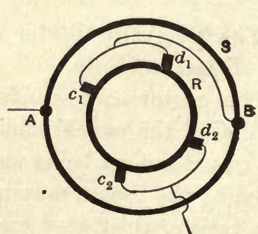


Fig. 5

4. *The Compensated Single-Phase Series Motor.*

This type of motor is represented under its two forms by Figs. 4 and 5. Such a motor works at every speed with good efficiency. The power factor is equal to unity at normal speed, and magnetizing current may be delivered to the network, if desired.

5. *The Repulsion Motor, the Stator of Which Has a Distributed Winding.*

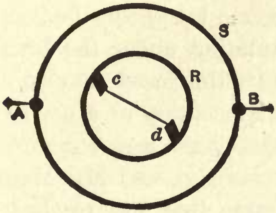


Fig. 6

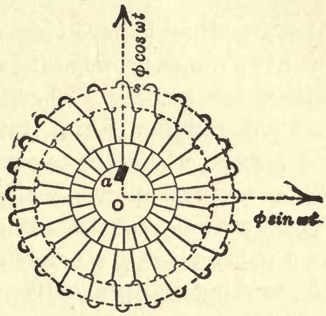


Fig. 7

This type of motor, represented by Fig. 6, has the general characteristics of the compensated series motor, but its power factor is lower and the leakage has in this motor a much worse influence.

All the machines of which I have just spoken have a common property regarding the commutation, viz., that if they are properly designed they work with a perfect commutation in the vicinity of synchronism, owing to the existence or the formation of a perfect rotary field. This property, which I have demonstrated for each machine successively, although at first questioned, is now recognized.

Let us consider (Fig. 7) a direct-current armature which is revolving under the action of a rotary field in a stator like that of an induction motor. The rotary field may be excited partly or completely, either from the stator or from the direct-current armature itself if this is traversed by alternating current.

Let us consider a section *s*, which is short-circuited under a brush *a*. The revolving field may be considered as the resultant of two alternating fields, the first one ϕ sin ωt in a direction perpendicular to $o\ a$; the second one ϕ cos ωt in the direction $o\ a$ itself.

Now the section s is the seat of two e.m.f.s. The first one is produced *in a static way* by the variation of the field, $\phi \sin \omega t$, and is equal to

$$e_1 = - \omega \frac{\psi}{2} \cos \omega t.$$

The second one is produced *in a dynamic way,* by the movement of the section s under the field $\phi \cos \omega t$, and is equal to

$$e_2 = \omega_1 \frac{\psi}{2} \cos \omega t,$$

if the armature is revolving at the angular speed ω_1.

These two e.m.fs. are opposite, and at synchronism ($\omega_1 = \omega$) counterbalance one another. The section s not being any longer the seat of any resultant e.m.f., the commutation under the brush a will be perfect, whatever the current under this brush may be.

This consideration leads easily to the conception of a device for avoiding sparking in the straight single-phase series motor. I wrote a paper upon this device a few years ago, and Mr. Maurice Milch, working independently on the same line, has reached the same result.

6. *The single-phase series motor with perfect commutation.*

We shall consider at first a single-phase series motor, the field of which is wound like a direct-current armature (Fig. 8). The motor

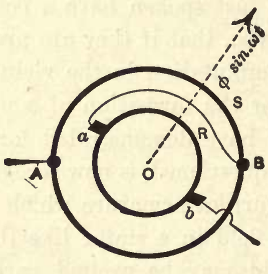


Fig. 8

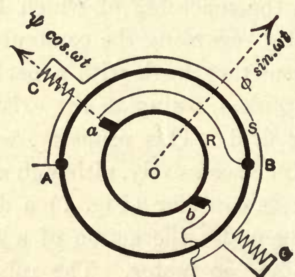


Fig. 9

being operated with continuous current, in order to obtain the best commutation the brushes must be located so that the resultant field of the motor $O\ \phi \sin \omega t$ is perpendicular to the line $a\ b$. When operated with single-phase current, if the induction is low enough, the power factor of the motor will be pretty high. In order to reverse the direction of rotation of the motor without shifting the

brushes, it will be possible to change the position of the terminals A B on the periphery of the stator.

Such a construction represents the best it is possible to obtain with the straight single-phase series motor, as I pointed out two years ago at a time when polar projections were still used.

But for the single-phase series motor there is no speed for which a perfect commutation is secured. The variation of the field of the motor induces at any speed an e.m.f. in the short-circuited sections, and owing to this very important reason, I think the series motor is, for larger capacities, inferior to the repulsion motor and to the compensated type.

Yet we can improve it in this way: An auxiliary field $\Psi \cos \omega t$ is produced above the short-circuited sections, which field lags 90 deg. behind the main field, $\phi \sin \omega t$, of the motor. (See Fig. 9.) Conforming with the explanation I have given above, it is easy to see that the new e.m.f. induced in the short-circuited sections *in a dynamic way* by the movement of these sections under the auxiliary field $\Psi \cos \omega t$, may counterbalance at a certain speed the e.m.f. induced in a static way by the variation of the main field $\phi \sin \omega t$.

The auxiliary field may be excited with special coils $c\ c$ shunt connected to the motor, these coils encompassing only a few slots.

We realize now that four types of motors are possible for single-phase traction: The repulsion type, the straight series motor, the compensated type, and the type with an auxiliary field. The future will decide which is the best.

CHAIRMAN DUNCAN: **The next paper will be on "The Theory and Operation of Repulsion Motors," by Mr. Bragstad, and will be abstracted by Mr. Steinmetz.**

SINGLE-PHASE RAILWAY MOTORS.

BY FRIEDRICH EICHBERG.

The standard direct-current railway has probably been developed to its final stage. The combination of alternating current for the transmission of power, rotary converters for the conversion into direct-current, and direct-current car motors, is not, however, an economical solution except in rare cases. Recognizing this fact, Brown & Boveri (Burgdorf-Thun) and Ganz & Company (Valtelina line) took up the direct application of polyphase alternating currents. But even if the polyphase system has achieved practical success in special cases, it has not been proven thereby that the polyphase motor furnishes a universal solution of the electric railway problem. It is not necessary here to repeat all the objections that European and American engineers have brought forward in numerous discussions against the polyphase motor. The multiple trolley for the collection of current, which is unavoidable in the polyphase system, leads to complications in the overhead work and sets narrow limits to the line voltage available. For short roads (lines between neighboring cities) the polyphase system, moreover, leads to excessive cost in the installation of the conducting system. Add to this that the polyphase motor, by reason of its characteristic speed-curve, which resembles that of a shunt-wound motor, is almost or quite unfit for railway purposes. It cannot be disputed that it is possible to operate on schedule time upon special lines with a favorable profile but this proves nothing as to the general applicability of the polyphase motor.

For two years, as is well known, efforts have been made to apply the single-phase motor to railway purposes. B. J. Arnold, with his electro-pneumatic system and the Oerlikon Company with the Ward-Leonard system, offered only incomplete solutions of the problem of applying single-phase current to railways. The first announcement of the direct application of single-phase motors came from Lamme, of Pittsburg, and was followed soon after by the publication of Finzi in Milan. The former used a frequency of 16, and the latter 18 cycles per second. Both have built series

motors similar to the direct-current series motor. The former uses, for the compensation of the armature reaction, short-circuited windings, which are applied in the field-magnet coils and whose axis coincides with that of the brushes; the latter uses slots in the poles for the diminution of the armature reaction.

Later the work of G. Winter (see *Elektrotechnische Zeitschrift,* 1904, No. 4), of Vienna, became known to the writer. This furnished the basis of the system worked out by the Union, and especially by the Allgemeine Elektricitäts-Gesellschaft. This system, which forms the subject of this paper, has been put into operation on the Niederschöneweide-Spindlersfeld line under the management of the Royal Prussian State Railway, and on the Stubaital line near Innsbruck, which was opened on July 31, 1904. The first line operates with 6000 volts and 25 cycles, and the second with 2350 volts and 42 cycles.

In perfecting this single-phase system, the motor of course played the chief part. In a lesser degree the controlling apparatus and those devices which become necessary in the direct application of high tension to the car were also of importance.

In regard to the motor of the Winter-Eichberg system, it unites the properties of the ordinary alternating-current series motor with those of the repulsion motor. Its characteristic features are the following:

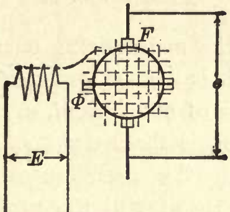
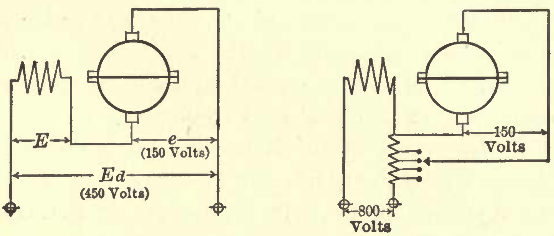


FIG. 1.

In the motor, in addition to its own magnetic field (F), there is developed as in the repulsion motor, a cross-field, Φ which, at synchronism, is about as strong as the magnetic field F, from which it differs in phase by 90 deg. This means that when the motor is near synchronism a complete rotary field is established, the field being less developed below or above synchronous speeds. On account of the cross-field developed in the motor, the short-circuited e.m.f. under the brushes diminishes with increasing speed, becomes nearly zero at synchronism and then increases again with increasing speed.

In regard to armature voltage, these motors are essentially similar to the ordinary series motor. In both the tension per commutator segment may not exceed a certain value and, according to the size of the motor, the armature voltage will therefore lie between 100 and 200 volts. In the ordinary series-motor, in which the working voltage appears in the armature, the working voltage would therefore not exceed 200 volts. It is otherwise with our motor. Since the armature is short-circuited along the working axis and the working voltage appears only in the stator field windings, the voltage supplied to the motor may be as great as desired. But even for the case where the excitation is inserted in series with the stator winding (Fig. 2), the entire working voltage (E) is in the same proportion to the armature voltage (e) at rest as the entire volt-ampere input is to the volt-amperes for magnetization at rest.



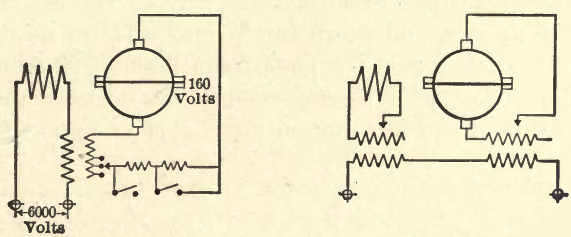
FIGS. 2 AND 3.

Let us suppose that the magnetizing current is one-third of the armature current, which is a good practical mean; then the working voltage in the motor of our system, even with the direct introduction of the excitation, is three times as high as in the ordinary series motor. Through the insertion of a small transformer (Fig. 3) one can increase at will the proportion of the working voltage to the armature voltage without great expense (Figs. 2 and 3).

The excitation by means of the armature in combination with the cross-field yields an e.m.f. which is 90 deg. ahead of the working e.m.f. and directly opposite to the e.m.f. of self-induction. This wattless counter e.m.f. gives the motor the well-known rapidly rising $\cos \phi$ curve. (See *Elektrotechnische Zeitschrift,* 1904, No. 4.) Our first 100-hp motor had, with a 3-mm air-space on each side, a power factor of 0.9 even at 70 per cent of synchronism. Even more important is the fact that this good power factor is obtained with a number of ampere-turns per cm almost twice as

great as in the ordinary alternating-current motors. From this results the possibility of building a very powerful motor for a given armature diameter and external dimensions.

Another characteristic property of our system is that the field can be controlled independently of the voltage in the working windings. In every alternating-current commutator motor there are magnetic losses in the coils short-circuited by the brushes. Through the possibility of adjusting this field in proportion to the stator current, one can keep these losses under the brushes within such limits as will permit the commutator and the brush-holders easily to conduct away the resulting heat. By varying the field one can, for a given working voltage, give the motor a variable characteristic. The separate characteristic curves will then be somewhat related as the curves of a 3-, 4-, 5- and 6-winding motor. Control independent of this naturally is possible and also control of the load voltage. The accompanying diagrams give examples of the control as carried out in practical cases. In Fig. 4 the primary voltage is not regulated and only the secondary winding of the exciting transformer is altered.

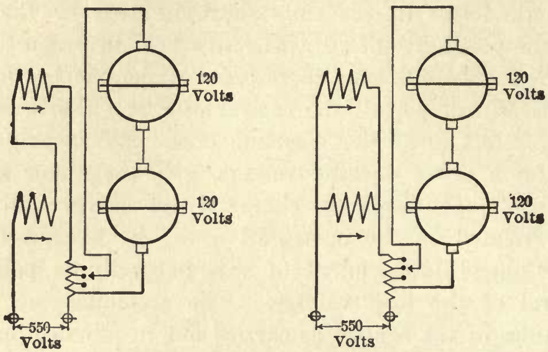


FIGS. 4 AND 5.

The absence of any primary regulation in the high-tension circuit offers the special advantage that only low-tension circuits will have to be opened or closed when the car is to start, reverse or alter its speed. A still more complete solution is shown in Fig. 5, the stator circuit as well as the exciter circuit being regulated. This method of connection is less advantageously applied to high-tension motors, because the high-tension circuits generally can not be readily altered in operation.

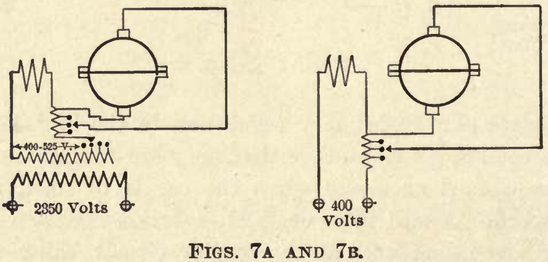
The third diagram (Figs. 6a and 6b) shows a method of control which, although not quite so complete as that of Fig. 5, is yet of value for small low-tension cars, and which will shortly be put into operation on a short Belgian road. The scheme of

Fig. 5, with the modification represented in Fig. 7, was installed on the Stubaital line near Innsbruck, now in operation, which is at times operated at 2350 volts and at other times at 400 volts. The direct insertion of the excitation in the stator circuit (Fig. 2) in which the control is effected by ohmic or inductive resistances



FIGS. 6A AND 6B.

with the eventual application of series-parallel regulation, is possible for small cars, and hence chiefly applicable to short railway lines. In the latter case the motors can be built simply for 550 volts. Motors for 550 volts connected in this manner are already in operation, and will also run on direct-current lines. (Figs. 7a and 7b.)



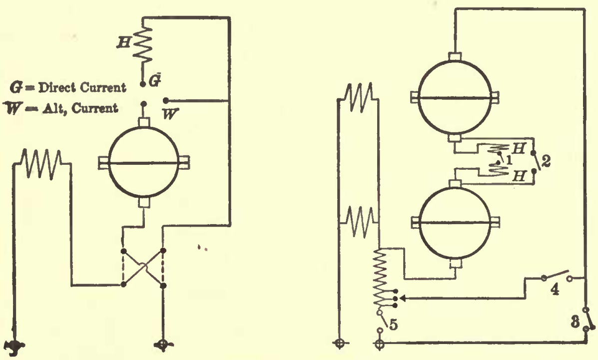
FIGS. 7A AND 7B.

The possibility of running an alternating-current motor with direct current is of great importance in practical application. Ordinary series commutator motors, which are built on the compensated system of Deri, can of course be run both on direct-current and alternating-current circuits. The voltage for the direct-current motor is 1½ to 2 times higher than the armature

voltage with alternating current. Since, as we have shown above, the alternating-current voltage, which in our motor system can be directly applied, may be three times greater than the armature voltage, the ratio of direct-current to alternating-current voltage will be, not as in the series motor 3:1½ or 3:2, but 3:3 to 1½ or 2; that is, the direct-current voltage will be about half that of the alternating-current voltage. This allows, for example, the running with direct currents with motors connected in series, and with alternating current with the motors connected in parallel, but in the former case at less speed. This corresponds to the case in common practice where cars which travel over interurban stretches at high speed transfer to the direct-current systems of cities, where lower speed is demanded. There are various ways of running, with a motor connected according to Fig. 1, on direct-current circuits. The method which has proved itself most practical is represented in Fig. 8. In the direction of the diameter of the exciter axis a winding is applied which counteracts and opposes the armature ampere-turns. The stator field windings then produce a magnetic field with direct current, and the exciting windings on the armature represent with direct current the working ampere windings. The field saturation in direct current working is then somewhat greater than with alternating current, while the density in the armature is somewhat less. These properties are extraordinarily favorable for practical operation. The auxiliary winding (h) is inserted only when operating with direct current. In order to make better use of the armature, the field windings of two motors can be connected in parallel in the direct-current circuit, while in order to be able to operate at 500-550 volts with direct currents, the armatures can be connected in series. These conditions are represented in Fig. 9. In the alternating-current system, one can operate according to the method of either Fig. 3 or Fig. 6. If operated according to plan 3, then with alternating currents the connections 2, 4, 5 are closed and 1 and 3 are open. With direct current, 1 and 3 are closed, and 2, 4 and 5 are open.

The motor system which I have above briefly described will not be the only one in the field. I can not, however, undertake to pass an unbiased opinion upon the different systems possible. I can only briefly mention the reasons why, in my opinion, the alternating-current commutator motor, which has been long known in two general types, namely, the ordinary series motor and the

repulsion motor, is not to be considered of equal value to the system above described. The ordinary series motor possesses, even if it is compensated, no cross-field; and it has no rotary field. The short-circuit losses under the brushes do not decrease with increasing speed, and the power-factor increases much slower with the speed. The maximum working voltage for which it can be built is 200 volts. When a short circuit takes place in the field winding of the series motor, the motor becomes inoperative. Multipolar machines with series windings on the armature, if provided with the device shown in Fig. 1, can have an entire field coil short-circuited without the motor becoming inoperative. The separate field coils behave like transformers inserted in series. Any one of these can always be short-circuited; the others then receive correspondingly more voltage.



FIGS. 8 AND 9.

The repulsion motor when contrasted with the arrangement of Fig. 1 has the disadvantage that its reversal is possible only by the application of a second field-winding, or of several sets of brushes, or of reversible brushes. Its power-factor is poorer, and for its control there remains only either the method of primary voltage control, the opening of short circuits, or finally of brush reversal.

The disadvantage of the type represented in Fig. 1, as compared with the series and repulsion motor, consists in the employment of two exciter brushes, which doubles the number of brushes in multipolar systems. These exciter brushes give rise to no difficulties with respect to short-circuit losses; as I have shown (*Elektrische Bahnen,* Vol. 2, 1904), these short-circuit losses do not occur with exciter brushes. They carry moreover only one-

third to one-fourth of the entire short-circuit current. On the other hand, the motor of Fig. 1, as compared with the compensated series motor and the repulsion motor with the double field-winding, offers the constructional advantage of only one field phase, which guarantees good economy and great simplicity. In high-tension motors, the increased certainty of operation in consequence of the absence of cross windings must be considered. Motors for either direct-current or alternating-current working provided with the auxiliary winding (h), which plays the part of the compensation winding of the compensated series motor, can therefore only be operated advantageously with low-tension alternating currents.

The results of more than a year's operation on the 6000-volt Niederschöneweide-Spindlersfeld line, on which during a great part of the day four 100-hp motors haul a 160- to 170-ton train, and on which daily two motors handle a 100-ton train, prove that the alternating-current motor is adapted to the heaviest traffic. Moreover, the direct application of 6000 volts to the car has been demonstrated to be entirely safe.

The Stubaital line, which has been running since July 31, 1904, at 42 cycles and 2350 volts, has introduced an advanced practice for small roads, an advance which exceeds the boldest expectations of the year 1902. At that time it seemed as though only very low frequencies could be used. In the case of many roads running in connection with existing power stations operating with 40-50 cycles, the possibility of using these frequencies limits the availability of alternating-current traction. Moreover, the possibility of operating also with direct current makes the alternating-current commutator motor in a certain sense a universal motor, and places it, as regards its main features, far above the direct-current commutator motor, which really represents only a special case of the alternating-current commutator motor.

THEORY AND OPERATION OF THE REPULSION MOTOR.

BY O. S. BRAGSTAD.

Commutator motors for alternating current have become of great interest within recent years. The main reason for this is the demand for a motor for single-phase alternating current for the operation of electric railways; but such motors will also find a broad field for other purposes where speed regulation is required. Of special interest in the older forms of alternating commutator motors is the repulsion motor, important in itself as also in that it marks a transition to the different forms of compensated motors.

In the following I will develop a general theory of the repulsion motor, and that under the usual assumptions that the magnetic resistance is constant for all magnetic circuits, and that the iron losses are proportional to the square of the induction. We will not consider the processes under the commutator brushes and in the armature coils short-circuited by the brushes.

PRINCIPAL EQUATION.

Fig. 1 shows the diagram of the motor. W_s is the stator and W_r the rotor winding. The angle of displacement relative to the shaft, $Y - Y$, of the stator winding is a. We further take:

$\underset{\cdot}{I}_s$ the stator current according to strength and phase,

$\underset{\cdot}{I}_r$ the rotor current according to strength and phase,

$\underset{\cdot}{E}_s'$ the induced e.m.f. according to strength and phase, in the stator winding, we get the following relation:[1]

$$^{1)}\underset{\cdot}{E'}_s = - Z_a (\underset{\cdot}{I}_s + \underset{\cdot}{I}_r \cos a) = \underset{\cdot}{I}_m z_a.$$

In this we assume the effective number of windings of the stator winding and of the rotor winding to be alike. $Z_a = r_a - j x_a$ can be designated as the exciting impedance of the motor and is given through the magnetic resistance of the main power current of the same, whereby r_a is so determined, that $E'^2_s \frac{r_a}{r_a^2 + x_s^2} = E'^2_s \frac{r_a}{Z^2_a}$ is

1. The period below the letter indicates that the value is a *vector* of determinable phase.

equal to the iron effect. $\dot{I}_m$ is the resulting current in the Y axis, or the magnetizing current in this axis. In the rotor winding there is induced between the brushes through the same power current:

1). Statically $\dot{E}'^{r}{}_{y} = \dot{E}'_s \cos a = -Z_a(\dot{I}_s + \dot{I}_r \cos a) = -Z_a \dot{I}_m \cos a$.

2). Dynamically through the rotation:

$$\dot{E}'_{ryd} = -j\frac{u}{c}\dot{E}_s \sin a = \frac{u}{c} j Z_a(\dot{I}_s + \dot{I}_r \cos a) \sin a = \frac{u}{c} j Z_a \dot{I}_m \sin a$$

where u is the number of periods of the rotor rotation.

c, number of periods of the current,

$j = \sqrt{-1}$.

The prefixed sign depends on the direction of rotation chosen.

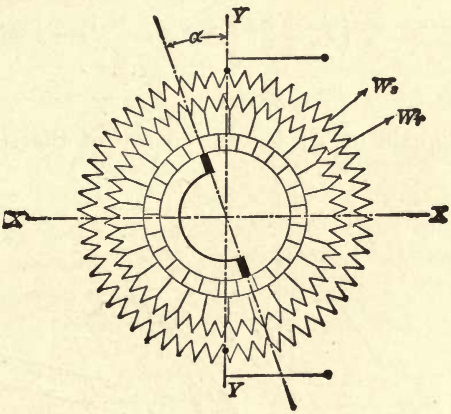


FIG. 1.

The rotor current generates a power current in the X — axis, perpendicularly to the axis of the stator winding. The e.m.f. induced by this power current is between the brushes:

1). Static

$$3) \quad \dot{E}'_{rx} = -Z_a \dot{I}_r \sin^2 a.$$

2). Dynamic, through the rotation

$$4) \quad \dot{E}'_{rxd} = j\frac{u}{c}\dot{E}'_{rx} \cos a = -\frac{u}{c} j Z_a \dot{I}_r \sin a \cos a.$$

The prefixed sign must be the reverse in equation 4 to what it is in equation 2.

From 2 and 4 follows

$$\dot{E}'_{ryd} + \dot{E}'_{rxd} = j\frac{u}{c} Z_a \dot{I}_s \sin a.$$

The field generated by the rotor current $\dot{I}_r$ thus produces no dynamic e.m.f., which also follows from the fact that the same runs along the brushes.

The entire e.m.f. induced in the rotor must be equal to the rotor current, $\dot{I}_r$ times the impedance of the rotor winding, which we will designate by Z_r. We, therefore, have

$$-Z_a \dot{I}_s \cos a - Z_a \dot{I}_r \cos^2 a - Z_a \dot{I}_r \sin^2 a + \frac{u}{c} j Z_a \dot{I}_s \sin a = \dot{I}_r Z_r$$

$$\dot{I}_r (Z_a + Z_r) = -\dot{I}_s \left(\cos a - \frac{u}{c} j \sin a\right) Z_a$$

$$\text{I)}\ \dot{I}_r = -\frac{Z_a}{Z_t}\left(\cos a - \frac{u}{c} j \sin a\right) \dot{I}_s$$

and

$$\text{II)}\ \dot{E}'_s = -\left(Z_a - \frac{Z_a^2}{Z_t}\left(\cos^2 a - \frac{u}{c} j \sin a \cos a\right)\right) \dot{I}_s$$

where

$$Z_t = Z_a + Z_r.$$

Let us designate by Z_s the impedance of the stator winding;

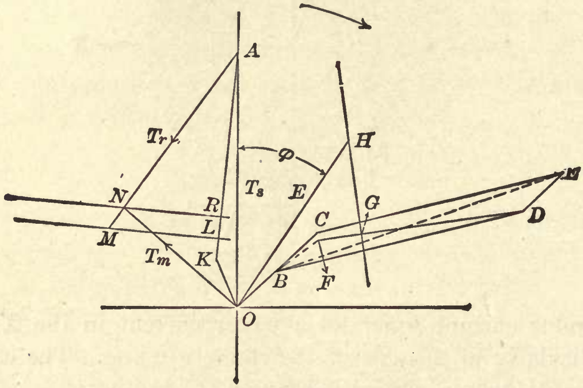


FIG. 2.

then the corresponding e.m.f. is equal to $-\dot{I}_s Z_s$, and the entire e.m.f. in the stator winding

$$\dot{E}' = \dot{E}'_s - \dot{I}_s Z_s.$$

Or if we introduce instead of the e.m.f. the terminal pressure, $\dot{E} = -\dot{E}'$, we have

$$\text{III)}\ \dot{E} = \dot{I}_s \left(Z_s + Z_a - \frac{Z_a^2}{Z_t}\left(\cos^2 a - \frac{u}{c} j \sin a \cos a\right)\right).$$

From this we get for a given constant stator current $I_s = \dot{I}_s$, the pressure diagram shown in Fig. 2. We assume the direction of

rotation of the vectors to be to the right and carry $OA = I_s$ onto the vertical axis. If we further have

$$OB = I_s Z_s$$
$$OC = DE = I_s Z_r$$
$$BD = CE = I_s Z_a$$

we have

$$BE = I_s (Z_a + Z_r) = I_s Z_t$$
$$FD = \frac{Z_a^2}{Z_t} I_s \text{ and } BF = \frac{Z_a Z_r}{Z_t} I_s$$

whereby we make the triangle BFD similar to the triangle BCE. We determine a point G on the straight line FD, so that $\frac{DG}{DF} = \cos^2 a$, draw a perpendicular line to DF at G and make $GU = \frac{u}{c} DF \sin a \cos a$. OU then represents the terminal pressure E of the motor for the respective number of revolutions u, and φ is the angle of lag of the current. At standstill of the motor $(u = o)$ point U coincides with G. OG is, therefore, the terminal pressure at standstill. With increasing positive speed the terminal point of the pressure vector OU moves upwardly on the perpendicular. When reversing the direction of rotation, the point moves downwardly. The machine is then converted into a generator.

Through equation 1 we can also easily find the rotor current I_r in the diagram. We make similar the triangles OKA, BCE, and BFD,

$$\frac{AL}{AK} = \cos a$$

and set up at point L a vertical line LM on AK. On this vertical line we mark off the distance $LM = \frac{u}{c} \sin a \; AK$, then we have for the respective number of revolutions u $AM = I_r$ according to quantity and phase. The terminal point of the vector I_r moves with a variable number of revolutions on a straight line similarly to the vector of the terminal pressure. If we make $AN = AM \cos a$, then $ON = I_s + I_r \cos a = I_m$ (see equation 1). ON thus represents the magnetizing current. With a variable number of revolutions u, point N moves on a straight line NR perpendicular to AK, and $AR = AK \cos^2 a$. It is seen that the two figures, $OKRAN$ and $BFGDU$, are alike, and that every length of the second has developed from the corresponding length of the first through multiplication by z_a and rotation about an angle equal to

arc by $\frac{x_a}{r_a}$. Furthermore, the latter figure is displaced from the initial point by the length $OB = I_s Z_s$.

Whilst in a series motor with constant current the field remains constant and the e.m.f. proportional to the speed is dynamically developed through the rotation speed of the induced (armature) winding, we have in the repulsion motor in the primary winding, because the same is stationary, only a statically induced e.m.f. and the change of the same with the speed is caused by a corresponding change of the field in the axis of the stator winding. This change is proportional to GU in the diagram. The field in the X axis is proportional to $I_r \sin a$ and likewise increases with the speed.

Moment of Rotation, Output, and Degree of Efficiency.

The moment of rotation which acts on the armature is obtained if we multiply the pressure, produced in an axis of the armature winding through the static induction, by the current component displaced thereto by 90 deg. in the second perpendicular axis. The moment of rotation is then obtained, expressed in the number of watts which the same would put out at synchronism. If we arbitrarily assume the two vertical axes, we must as a general rule carry out two multiplications and add up the two products.

Here we must consider every axis once as current axis and then as pressure axis. If, however, we so chose the two perpendicular axes that either the current or the pressure becomes zero in one axis, then one of the two products disappears and we need make but one multiplication.

In the present case we put the one axis through the armature brushes and the second one perpendicularly thereto. The current in the direction of the second axis is then zero, and we only need to form the product from the pressure in the perpendicular direction to the armature brushes and the rotor current displaced relative thereto by 90 deg.

This pressure is

$$\dot{Z}_a \dot{I}_s \sin a = \frac{z_a}{\dot{Z}_t} \dot{I}_s \dot{Z}_t \sin a.$$

and the rotor current is

$$\dot{I}_r = -\frac{Z_a}{Z_t} \left(\cos a - \frac{u}{c} j \sin a\right) \dot{I}_s$$

The product is obtained as the imaginary part of the product, after having changed the prefixed sign of the imaginary current

component. We so chose the phase of $\dot{I}_s$, that $\frac{Z_a}{Z_t}\dot{I}_s$ becomes actually equal to $\frac{z_a}{z_t} I_s$, where

$$z_a = \sqrt{r_a^2 + x_a^2} \text{ and } z_t = \sqrt{r_t^2 + x_t^2}$$

The moment of rotation is then

$$D = \left(I_s \frac{z_a}{z_t}\right)^2, \text{imaginary part of } \left(-\cos a - \frac{u}{c} j \sin a\right)\left(r_t - j x_t\right) \sin a$$

$$\text{IV)}\ D = \left(I_s \frac{z_a}{z_t}\right)^2 \left(x_t \sin a . \cos a - \frac{u}{c} r_t \sin^2 a\right)$$

We can then determine by differentiation the brush angle a, for which the moment of rotation for a given current I_s becomes a maximum. We get

$$5)\quad \tan 2\,a = \frac{x_t}{r_t}\,\frac{c}{u}$$

At the start $u = o$, thus $\tan 2\,a = \infty$ $a = 45$ deg. With an increasing speed a is somewhat decreased. At synchronism $(u = c)$ we get

$$5\,a)\quad \tan 2\,a = \frac{x_t}{r_t}.$$

With $a = 45$ deg. the moment of starting is

$$6)\quad D_k = \left(I_s \frac{z_a}{z_t}\right)^2 \frac{x_t}{2}$$

and the moment at synchronism

$$7)\quad D_s = \left(I_s \frac{z_a}{z_t}\right)^2 \frac{x_t - r_t}{2}$$

The energy transformed into mechanical work is found simply by multiplying the moment of rotation by $\frac{u}{c}$. It is thus

$$\text{V)}\ W_m = \frac{u}{c} D = \left(I_s \frac{z_a}{z_t}\right)^2 \left(\frac{u}{c} x_t \sin a \cos a - \left(\frac{u}{c}\right)^2 r_t \sin^2 a\right).$$

According to equation III we have for the terminal pressure, if we put $\dot{I}_s = I_s$

$$\text{III}_a)\ \dot{E} = I_s \left(Z_s + Z_a - Z\left(\cos^2 a - \frac{u}{c} j \sin a \cos a\right)\right)$$

$$= I_s \left(Z_g - Z\left(\cos^2 a - \frac{u}{c} j \sin a \cos a\right)\right)$$

$$= I_s \left(r_g - r \cos^2 a + \frac{u}{c} x \sin a \cos a - j\left(x_g - x \cos^2 a - \frac{u}{c} r \sin a \cos a\right)\right)$$

$$=I_s\left(r_k+\frac{u}{c}x\sin a\cos a-j\left(x_k-\frac{u}{c}r\sin a\cos a\right)\right).$$

The following abbreviations have here been introduced:

$$\frac{Z_a{}^2}{Z_t}=Z=r-jx \quad \left(\text{constant section } FD \text{ in Fig. } 2\right)$$

$$Z_s+Z_a=r_s+r_a-j\,(x_s+x_a)$$

$$=Z_g=r_g-j\,x_g \quad (\text{constant section } OD \text{ in Fig. } 2)$$

$$Z_g-Z\cos^2 a=r_g-r\cos^2 a-j\,(x_g-x\cos^2 a)$$

$$=Z_k=r_k-j\,x_k \quad (\text{section } OG \text{ in Fig. } 2)$$

Z_k is the impedance of the motor at standstill (short-circuit impedance), and is dependent on angle a.

For $a=o$ we have

$$Z_k=Z_s+\frac{Z_a Z_r}{Z_t} \quad (\text{section } OF \text{ in Fig. } 2.)$$

With an increasing angle of displacement of the brushes, the terminal point of the vector Z_k moves on the straight line FD from F to D. For $a=90$ deg. we have

$$Z_k=Z_s+Z_a=Z_g \quad (\text{section } OD \text{ in Fig. } 2).$$

From equation V we can determine the number of revolutions u_e for which the output of the motor becomes naught. The same is

$$9)\qquad \frac{u_e}{c}=\frac{x_t}{r_t}\frac{\cos a}{\sin a}$$

For this no-load point we get the phase displacement φ_e by putting the above value of $\frac{u_e}{c}$ into equation IIIa. We get

$$10)\qquad \tan\varphi_e=\frac{x_k-\frac{x_t}{r_t}r\cos^2 a}{r_k+\frac{x_t}{r_t}x\cos^2 a}=\frac{x_e}{r_e}.$$

$Z_e=r_e-jx_e$ can be designated as the no-load impedance of the motor. We can also put

$$Z_e=r_g-\left(r-\frac{x_t}{r_t}x\right)\cos^2 a-j\left(x_g-\left(x+\frac{x_t}{r_t}r\right)\cos^2 a\right)$$

$$=Z_g-\left(r-jx\right)\left(1-j\frac{x_t}{r_t}\right)\cos^2 a$$

$$11)\qquad =Z_g-Z\left(1-j\frac{x_t}{r_t}\right)\cos^2 a$$

From this we immediately get the following construction of Z_e

(Fig. 3). We make $OB = Z_e$ and $BE = Z_t = r_t - j x_t$ equal to the geometrical sum of BD and DE, whereby $BD = Z_a$ and $DE = Z_r$. Thereupon we draw the line $DF = Z = \frac{Z_a^{\,2}}{Z_t}$ and set up at F, a vertical FS. The angle FDS becomes equal to $\operatorname{arc\,tan} \frac{x_t}{r_t}$ and $\frac{DT}{DS} = \cos^2 a$. OT is then the vector of the no-load impedance. The terminal point of the vector of the short-circuit impedance is G and this point is the projection of point T onto section $Z = DF$. For $a =$

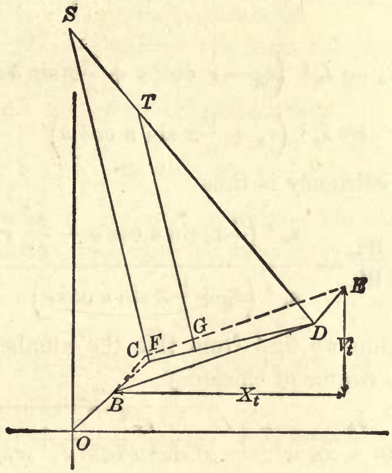


FIG. 3.

90 deg., $\cos a = o$, the no-load point S coincides with the short-circuit point G in point D. With the decrease of angle a, the no-load point moves toward S and the short-circuit point toward F.

From equation V we find the maximum output of the motor for a constant current, if

$$x_t \sin a \cos a - 2 \frac{u}{c} r_t \sin^2 a = o$$

12) $$\frac{u}{c} = \frac{1}{2} \frac{x_t}{r_t} \frac{\cos a}{\sin a}.$$

The maximum output with constant current, therefore, occurs when the motor has half of the no-load speed (see equation 9). This maximum output would be

13) $$W_{m\,max} = \left(I_s \frac{z_a}{z_t}\right)^2 \cdot \frac{1}{2} \frac{x_t^{\,2}}{r_t} \cos^2 a$$

If we introduce the number of revolutions for the maximum output into equation III_a), we have

$$E = I_s \left(r_k + \frac{1}{2} \frac{x_t}{r_t} x \cos^2 a - j \left(x_k - \frac{1}{2} \frac{x_t}{r_t} r \cos^2 a \right) \right.$$

Or in consideration of equation 10:

14) $$E = I_s \left(\tfrac{1}{2} (r_k + r_e) - j \left(\tfrac{1}{2} (x_k + x_e) \right) \right).$$

This result also follows directly from the fact that the point for maximum output lies in the middle between the short-circuit point and the no-load point.

The general expression for the electric power supplied to the motor is

15) $$W_e = I_s^{\,2} \left(r_g - r \cos^2 a + \frac{u}{c} x \sin a \cos a \right)$$
$$= I_s^{\,2} \left(r_k + \frac{u}{c} x \sin a \cos a \right)$$

The degree of efficiency is thus

16) $$\eta = \frac{W_m}{W_e} = \frac{z_a^{\,2} \left(\dfrac{u}{c} x_t \sin a \cos a - \dfrac{u^2}{c^2} r_t \sin^2 a \right)}{z_t^{\,2} \left(r_k + \dfrac{u}{c} x \sin a \cos a \right)}$$

By differentiation we find from this the number of revolutions for the maximum degree of efficiency

$$\frac{u}{c} = - \frac{r_k}{x \sin a \cos a} \pm \sqrt{\frac{r_k^{\,2}}{x^2 \sin^2 a \cos^2 a} + \frac{r_k x_t}{r_t x \sin^2 a}}$$

The negative prefix of the root would apply to the operation as generator. We here take the positive. The expression can be easily reduced to the following:

17) $$\frac{u}{c} = \frac{\sqrt{r_k r_e} - r_k}{x \sin a \cos a}$$

This expression for the most favorable number of revolutions introduced into equation 16 gives for the maximum degree of efficiency the following value:

18) $$\eta_{max} = \frac{z_a^{\,2}}{z_t^{\,2}} \; \frac{(2 r_k r_t + x_t x \cos^2 a) \sqrt{r_k r_e} - 2 r_t r_k r_e}{x^2 \cos^2 a \sqrt{r_k r_e}}$$

The values for the most favorable number of revolutions (17), and for the corresponding degree of efficiency (18) are, as is seen. independent of the chosen current strength and of the terminal pressure. If the current strength is assumed, we find the terminal pressure through the introduction of the respective number of

revolutions into equation III_a. We likewise obtain the output of the motor by introducing the number of revolutions into equation V.

Output Diagram with Constant Terminal Pressure.

The mode of operation of the motor, assuming a constant current, can be quite plainly seen in the pressure diagram of Fig. 2. This diagram is useless, however, when it is a question of examining the action of the motor with a constant terminal pressure. We will now also develop a diagram for this case.

In equation III_a we assume the terminal pressure to be real, in that we put $\dot{E} = E$ but we allow the current vector to take any arbitrary phase. Equation III_a then reads

$$III_b) \; E = \dot{I}_s \left(r_k + \frac{u}{c} x \sin a \cos a - j \left(x_r - \frac{u}{c} r \sin a \cos a \right) \right)$$

For the current $\dot{I}_s$ we will introduce the two components, the real one η parallel to e and the imaginary one ζ, perpendicular to e. We thus put

$$\dot{I}_s = \eta + j \xi$$

Because the imaginary must disappear on the right side of equation III_b), we have

$$19) \quad \xi \left(r_k + \frac{u}{c} x \sin a \cos a \right) = \eta \left(x_r - \frac{u}{c} r \sin a \cos a \right)$$

and from this

$$19_a) \quad \frac{u}{c} \left(\xi x + \eta r \right) \sin a \cos a = \eta x_k - \xi r_k$$

From this we can deduce the following two equations:

$$\eta \frac{u}{c} x \sin a \cos a = \frac{\eta^2 x_k - \xi \eta r_k}{\xi x + \eta r} x$$

$$\xi \frac{u}{c} r \sin a \cos a = \frac{\xi \eta x_k - \xi^2 r}{\xi x + \eta r} r.$$

If we introduce these two values into equation 19, we get:

$$\epsilon (\xi x + \eta r) = (\xi^2 + \eta^2) (r r_k + x x_k)$$

or

$$VI) \quad \dot{I}_s^2 = \xi^2 + \eta^2 = \epsilon \frac{\xi x + \eta r}{r r_k + x x_k}$$

If we consider ξ as abscissa and η as ordinate in a rectangular co-ordinate system, then this equation represents a circle. The

same goes through the initial point of the co-ordinates and has the radius

$$20)\qquad R = E\frac{\sqrt{r^2 + x^2}}{2\,(r\,r_k + x\,x_k)} = E\frac{z}{2\,(r\,r_k + x\,x_k)}$$

The co-ordinates of the central point are

$$21)\qquad \begin{cases} \text{Abscissæ } m = E\dfrac{x}{2\,(r\,r_k + x\,x_k)} \\ \text{Ordinates } u = E\dfrac{r}{2\,(r\,r_k + x\,x_k)} \end{cases}$$

With constant terminal pressure we thus have the current vector according to strength and phase as the distance from the initial point to a circle. By means of this circle we can follow the work in the motor. We will first consider the number of revolutions, or what is the same, the relation $\frac{u}{c}$.

According to equation 19_a we have

$$22)\qquad \frac{u}{c} = \frac{\eta\,x_k - \xi\,r_k}{\sin a \cos a\,(\xi\,x + \eta\,r)} = \frac{L_1}{\sin a \cos a\,L_2}$$

Here we have $\eta\,x_k - \xi\,r_k = L_1 = o$ a straight line through the initial point of the co-ordinate system. According to equation 19, $\frac{\eta}{\xi} = \frac{r_k}{x_k}$ with $u = o$. The straight line $L_1 = o$ thus goes through the short-circuit point of the motor. The short-circuit current is OK in Fig. 4.

$\xi\,x + \eta\,r = L_2 = o$ is likewise a straight line, which stands perpendicularly on the connecting line (central line) between the origin of co-ordinates and the central point of the circle. This line is, therefore, a tangent at the initial point. Every vector is a ray in a group of rays, and has the equation

$$\frac{u}{c}\sin a \cos a\,L_2 - L_1 = o.$$

For $u = c$ the equation of the ray (synchronous line) is $L_3 = \sin a \cos a\,L_2 - L_1 = \eta\,(r \sin a \cos a - x_k) + \xi\,(x \sin a \cos a + r_k) = o.$

For any point P of the circle, $\frac{u}{c}$ is the double relation between the four rays and the same is cut off on a transverse line, thus

$$\frac{u}{c} = \frac{\dfrac{a\,b}{a\,c}}{\dfrac{d\,b}{d\,c}} \qquad \text{(see Fig. 4.)}$$

If we draw the transverse line parallel to the straight line $L_2 = o$, then the double relation passes over into the single relation and we get

$$\frac{u}{c} = \frac{a^1 b^1}{d^1 b^1}$$

We can, therefore, read on the transverse line parallel to the straight line $L_2 = o$ the speed of rotation for every current.

The synchronous line $L_3 = o$ can be constructed as follows: Over the section $FD = z$ as diameter we describe a circle and mark off the brush angle $a = GDT$ in point D. The synchronous line then runs through point T. A perpendicular line from T onto section FD cuts the latter in point G; OG is the short-circuit impedance of the motor with the two components $r_k = r_g - r \cos^2 a$ and $x_k = x_g - x \cos^2 a$. The short-circuit line $L_1 = o$ thus goes through point G. The short-circuit point K on the diagram circle is an inverse point to point G, in that OK is proportional to $\frac{1}{OG}$. A modification of the brush angle a changes the size of the diagram circle and the position of the short-circuit point K as also the position of the synchronous line $L_3 = o$. If a is made so large, that the synchronous line becomes a tangent to the circle over FD, synchronous speed occurs with the smallest phase displacement. When G moves toward F, if, therefore, a is reduced, the short-circuit point K continually moves higher on the circle; the losses are thus increased. At the same time, however, the diameter of the diagram circle and therewith the maximum output of the motor are increased. The question as to the most favorable brush displacement angle can thus be answered in very many different ways according to the special result which is to be obtained. By means of the diagram in Fig. 4, we can easily find the most favorable brush position for a given case.

We will now see how we can represent the moment of rotation in the diagram. According to equation IV

$$D = \left(\frac{z_a}{z_t}\right)^2 I_s^{\,2} \left(x_t \sin a \cos a - \frac{u}{c} r_t \sin^2 a\right).$$

In accordance to the circle equation VI, we have however

$$I_s^2 = \frac{E\,(\xi\, x + \eta\, r)}{r\, r_k + x\, x_k} = \frac{2\,R}{z} (\xi\, x + \eta\, r)$$

and according to equation 22

$$\frac{u}{c} = \frac{\eta\, x_k - \xi\, r_k}{\sin a \cos a\, (\xi\, x + \eta\, r)} = \frac{L_1}{\sin a \cos a\, L_2}$$

Introducing this for the moment of rotation we get

$$
23)\quad \left\{
\begin{aligned}
D &= \left(\frac{z_a}{z_t}\right)^2 \frac{2\,R}{z}\, r_t \frac{\sin a}{\cos a}\Big(\xi\left(r_k + \frac{x_t}{r_t}\, x\cos^2 a\right) \\
&\qquad - \eta\left(x_k - \frac{x_t}{r_t}\cos^2 a\right)\Big) \\
&= \left(\frac{z_a}{z_t}\right)^2 \frac{2\,R}{z}\, r_t \frac{\sin a}{\cos a}\left(\xi\, r_e - \eta\, x_e\right) \\
&= \left(\frac{z_a}{z_t}\right)^2 \frac{2\,R}{z}\, r_t \frac{\sin a}{\cos a}\, L_4
\end{aligned}
\right.
$$

The straight line $\xi\, r_e - \eta\, x_e = L_4 = o$ is the no-load line, the construction of which we have given in Fig. 3.

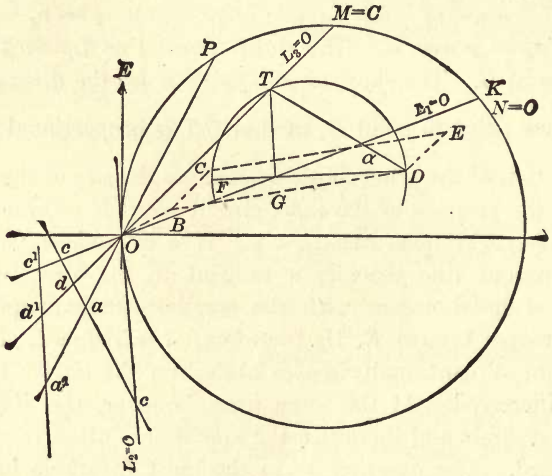


FIG. 4.

The moment of rotation is at any point proportional to the distance of the same from the no-load line. In short-circuit the current is

$$I_k^2 = \frac{E^2}{(r_g - r\cos^2 a)^2 + (x_g - x\cos^2 a)^2} = \frac{E^2}{r_k^2 + x_k^2}$$

The starting moment is, therefore,

$$24)\qquad D_k = \left(\frac{z_a}{z_t}\right)^2 I_k^2\, x_t \sin a \cos a$$

$$= \left(\frac{z_a}{z_t}\right)^2 \frac{E^2\, x_t \sin a \cos a}{(r_g - r\cos^2 a)^2 + (x_g - x\cos^2 a)^2}$$

Hereby the measure for the determination of the moment of rotation is given by the distance from the no-load line for every point.

We will now introduce the relation between the moment of rotation in watts relative to synchronism and the introduced watts. This is

25) $$\delta = \frac{D}{W_e} = \left(\frac{z_a}{z_t}\right)^2 \frac{2\,R\,r_t}{z\xi} \; \frac{\sin a}{\cos a} \; \frac{\xi\, r_e - \eta\, x_e}{\eta}$$

At starting we have

26) $$\delta_k = \frac{D_k}{W_{ek}} = \left(\frac{z_a}{z_t}\right)^2 \frac{x_t}{r_k} \sin a \cos a.$$

It is seen that δ is the double relation in a group of vectors consisting of the abscissæ axis ($\eta = o$), the no-load line ($L_4 = o$) and the short-circuit line ($L_1 = o$). Because in this group of

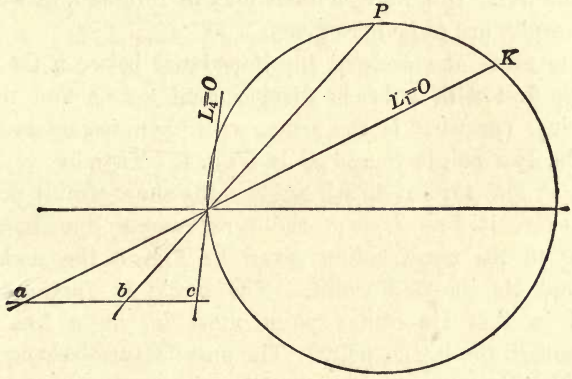


FIG. 5.

vectors the double relation is given for the short-circuit line as equal δ, the same can be at once determined for any vector δ. If in Fig. 5, $L_1 = o$ is the short-circuit line and $L_4 = o$ the no-load line, if further the straight line ac is drawn parallel to the abscissæ axis, we have for a vector through the center point P

$$\frac{\delta}{\delta_k} = \frac{c\,b}{c\,a}$$

Thus if we make $ca = \delta_k$, we have

$$\delta = cb.$$

Because now, through the two constructions given in Figs. 4 and 5, the values $\frac{u}{c}$ and $\delta = \frac{D}{W_e}$ can be read off for every point of the

diagram by carrying the current vector to the respective point, we have also given us at once for every point the efficiency of the motor; for the efficiency is

$$27) \qquad \eta = \frac{W}{W_e} = \frac{\frac{u}{c} D}{W_e} = \frac{u}{c} \delta.$$

We thus need only multiply the two values read off.

If the diagram is to be constructed for a motor only *planned,* the separate reactances and resistances can be calculated and they need only be introduced properly into the given formula. Some abbreviations and omissions are then permissible not introduced here, on account of their general character.

If the motor is already constructed, the diagram can be determined by some measured values and we can thus get at the mode of working of the motor without the necessity of carrying out a complete brake test. Different methods may be followed, of which only a few examples are to be here given.

If we measure at standstill the impedance between the primary terminals, first with a brush displacement $\alpha = o$ and then with $\alpha = 90$ deg. (or what is the same, with open secondary circuit), we get the two points F and D in Fig. 4. Thereby we have the line $L_2 = o$, and for any brush angle α the short-circuit point with the short-circuit line $L_1 = o$, the synchronous line $L_3 = o$, and according to the construction given in Fig. 3 the no-load line $L_4 = o$ and the no-load point. The circle is furthermore determined in that its center point must lie on a line parallel to FD through the initial point. The only feature lacking in order to make the diagram complete is the scale to give us the moment of rotation and thereby the determination of the degree of efficiency. The same can be most simply obtained by measuring the torque D^k at standstill and with any brush angle α. If now we put according to equation 26

$$\delta_k \frac{D_k}{W_{ek}} = a\,c \qquad \text{(see Fig. 5)}$$

where W_{ek} is the electric power supplied at standstill with the respective brush position α, then for any brush position and any speed $\frac{u}{c}$, for which the power supplied is W_e, the moment of rotation $D = \delta\, W_e = bc\, W_e$

and the degree of efficiency

$$\eta = \frac{u}{c} \cdot \frac{D}{W_e} = \frac{u}{c}\, \delta = \frac{u}{c} \cdot b\,c.$$

For another brush angle α^1 with the short-circuit resistance $r_k{}^1$ and the section a^1c^1 between the short-circuit and no-load line we have according to equation 26

$$\frac{\delta_k}{\delta_k{}^1} = \frac{r_k}{r_k{}^1} \frac{\sin \alpha^1 \cos \alpha^1}{\sin \alpha \cos \alpha}$$

We would thus have to put for this angle

$$\delta_k{}^1 = a^1\, c^1 = \frac{r_k}{r^1{}_k} \frac{\sin \alpha^1 \cos \alpha^1}{\sin \alpha \cos \alpha}\, a\, c$$

$$D = \delta^1\ W_e = b^1\, c^1\ W_e.$$

From this we must determine the moment of rotation and the efficiency for any brush angle α^1, when the moment of torque for an angle α has been determined.

Maximum Output with Constant Terminal Pressure.

In accordance with equations 22 and 23, we have

$$\frac{u}{c} \frac{\eta\, x_k - \xi\, r_k}{\sin \alpha \cos \alpha\, (\xi\, x + \eta\, r)} = \frac{2\ R}{z} \frac{\eta\, x_k - \xi\, r_k}{\sin \alpha \cos \alpha\, I_s{}^2}$$

$$D = \left(\frac{z_a}{z_t}\right)^2 \frac{2\ R}{z} r_t \frac{\sin \alpha}{\cos \alpha} \left(\xi\, r_e - \eta\, x_e\right).$$

We thus have

$$W_m = \left(\frac{z_a}{z_t}\right)^2 \left(\frac{2\ R}{z}\right)^2 \frac{r_t}{\cos^2 \alpha} \frac{(\eta\, x_k - \xi\, r_k)\ (\xi\, r_e - \eta\, x_e)}{I_s{}^2}$$

If we put

$$\cos \varphi_k = \frac{r_k}{z_k}\ ; \ \sin \varphi_k = \frac{x_k}{z_k}$$

$$\cos \varphi_e = \frac{r_e}{z_e}\ ; \ \sin \varphi_e = \frac{x_e}{z_e}$$

$$\cos \varphi = \frac{\eta}{I_s}\ ; \ \sin \varphi = \frac{\xi}{I_r}$$

then φ_k = angle between short-circuit line and ordinate axis

φ_e = angle between no-load line and ordinate axis

φ = phase displacement of the current

and we have

28) $$W_m = \left(\frac{z_e}{z_t}\right)^2 \left(\frac{2R}{z}\right)^2 \frac{r_t\, z_k\, z_e}{\cos^2 \alpha} \sin\,(\varphi_k - \varphi)\, \sin\,(\varphi - \varphi_e)$$

The mechanical output is, therefore, a maximum, when

$$\varphi_k - \varphi = \varphi - \varphi_e$$

or

29) $$\varphi = \frac{\varphi_k + \varphi_e}{2}.$$

The output of the motor is a maximum, when the phase displacement angle has the arithmetical mean value of the two-phase displacement angles at short-circuit and at no-load. If we put down the short-circuit line as

$$\eta \frac{x_k}{z_k} - \xi \frac{r_k}{z_k} = o$$

and the no-load line as

$$\xi \frac{r_e}{z_e} - \eta \frac{x_e}{z_e} = o$$

then the equation of the current vector at maximum output is

30) $$\xi \left(\frac{r_e}{z_e} + \frac{r_k}{z_k}\right) - \eta \left(\frac{x_e}{z_e} + \frac{x_k}{z_k}\right) = o$$

or

31) $$\xi \,(r_e\, z_k + r_k\, z_e) - \eta \,(x_e\, z_k + x_k\, z_e) = o$$

We combine this with the circle equation

$$\xi^2 + \eta^2 = E \frac{\xi\, x + \eta\, r}{r\, r_k + x\, x_k}$$

and we get

$$\eta \left((x_e z_k + x_k\, z_e)^2 + (r_e\, z_k + r_k\, z_e)^2\right)$$

$$= E \frac{x\,(x_e\, z_k + x_k\, z_e) + r\,(r_e\, z_k + r_r\, z_e)}{r r_k + x x_k}\Bigg).$$

$$(r_e z_k + r_k z_e) = E\, \frac{z_k\,(x x_e + r r_e) + z_e\,(x x_k + r r_k)}{r r_k + x x_k}\,(r_e\, z_k + r_k\, z_e)$$

We have

$$x x_e + r r_e = x\,(x_k - \frac{x_t}{r_t}\, r \cos^2 a) + r\,(r_k + \frac{x_t}{r_t}\, x \cos^2 a) = x x_k + r r_k$$

Hence

$$\eta = E\, \frac{(z_k + z_e)\,(r_e\, z_k + r_k\, z_e)}{(x_e\, z_k + x_k\, z_e)^2 + (r_e\, z_k + r_k\, z_e)^2}$$

$$\xi = E\, \frac{(z_k + z_e)\,(x_e z_k + x_k\, z_e)}{(x_e\, z_k + x_k\, z_e)^2 + (r_e\, z_k + r_k\, z_e)^2}$$

η and ξ are watt and wattless current at maximum output. The output factor with this output is

32) $$\cos \varphi = \frac{r_e z_k + r_k\, z_e}{\sqrt{(x_e\, z_k + x_k\, z_e)^2 + (r_e\, z_k + r_k\, z_e)^2}}$$

The number of revolutions with maximum output is found as follows

$$\frac{u}{c} = \frac{\eta\, x_k - \xi r_k}{\sin a \cos a\, (\eta\, r + \xi\, x)}$$

$$= \frac{x_k (r_e z_k + r_k z_e) - r_k (x_e z_k + x_k z_e)}{\sin a \cos a [r (r_e z_k + r_k z_e) + x (x_e z_k + x_k z_e)]}$$

$$= \frac{z_k (x_k r_e - r_k x_e)}{\sin a \cos a [z_k (r r_e + x x_e) + z_e (r r_k + x x_k)]}$$

$$= \frac{z_k (x_k r_e - r_k x_e)}{\sin a \cos a (z_k + z_e) (r r_k + x x_k)}$$

Now we have

$$\frac{x_k r_e - r_k x_e}{\sin a \cos a (r r_k + x x_k)} = \frac{x_t}{r_t} \cot a = \frac{u_e}{c}$$

where u_e is the number of revolutions at no-load (equation 9). Thus we have with maximum output

$$33) \qquad \frac{u}{c} = \frac{z_k}{z_u + z_e} \frac{u_e}{c}.$$

The moment of rotation with maximum output is

$$D = \left(\frac{z_a}{z_t}\right)^2 \frac{2R}{z} r_t \frac{\sin a}{\cos a} (\xi r_e - \eta x_e) \quad \text{(Equation 23)}$$

where for ξ and η we must introduce the current component for this maximum output. We then have

$$\xi r_e - \eta x_e = E \frac{(z_k + z_e)(r_e x_k - x_e r_k) z_e}{(x_e x_k + x_k z_e)^2 + (r_e z_k + r_k z_e)^2}$$

$$= z_k^2 z_e (z_k + z_e) \frac{r_e E \frac{x_k}{z_k^2} - x_e E \frac{r_k}{z_k^2}}{(x_e z_k + x_k z_e)^2 + (r_e z_k + r_k z_e)^2}$$

Here $E \frac{x_k}{z_k^2}$ and $E \frac{r_k}{z_k^2}$ are the current components when the motor is at standstill and the torque is

$$D_k = \left(\frac{z_a}{z_t}\right)^2 \frac{2R}{z} r_t \frac{\sin a}{\cos a} \left(r_e E \frac{x_k}{z_k^2} - x_e E \frac{r_k}{z_k^2}\right)$$

Consequently the moment of rotation for maximum output is

$$34) \quad \begin{cases} D = D_k \dfrac{z_k^2 z_e (z_k + z_e)}{(x_e z_k + x_k z_e)^2 + (r_e z_k + r_k z_e)^2} \\[2ex] \quad = D_k \dfrac{z_k (z_k + z_e)}{z (z_k z_e + x_k x_e + r_k r_e)} \end{cases}$$

The output itself is

$$35) \qquad W_{m\,max} = D \frac{u}{c} = D_k \frac{z_k^2 \cdot \frac{u_e}{c}}{z (z_k z + x_k x_e + r_k r_e)}$$

We finally find the efficiency for the maximum output

$$36)\qquad \eta = \frac{W_{m\,max}}{W_e} = \frac{D_k}{E^2} \frac{z_k{}^3 z_e \frac{u_e}{c}}{(r_e\, z_k + r_k\, z_e)\,(z_k + z_e)}$$

For the use of the formula indicated in the last section in considering a motor design, it is only necessary to make no-load measurements at standstill of the impedance Z_k and the torque D_k and at no-load, of the impedance Z_e and the number of revolutions u_e.

THEORY OF THE COMPENSATED REPULSION MOTOR.

BY ERNST DANIELSON.

Of late there has been a great deal written about the compensated repulsion motor, which fairly may be considered the most modern type of motor in the present electrical industry. Not only analytical but also graphical methods have been given for explaining its qualities. It appears, however, that a complete analytical treatment, considering the leakage — that is to say, formulas for the calculation of current, torque and lag with known voltage, brush position and speed — have not as yet been published. In this paper the author will present the formulas which are used by The Allmänna Svenska Elektriska Aktiebolaget of Westerås, Sweden, for figuring such motors, and which have given results in good agreement with actual tests.

It should be mentioned before entering into details, that in the following theory the magnetic losses are neglected and that accordingly the magnetic vector is considered the same as the resulting ampere-turns. When using the formulas given below, it is therefore necessary, when aiming at the utmost accuracy, to apply a correction for these losses.

Referring to Fig. 1, let $I_k \sin at$

be the current on short-circuit, assuming the direction as the position when the current is flowing *in the winding* from c to d;

$$a = 2\pi N; \quad (N = \text{frequency}).$$

This current creates leaking lines of force, viz., lines of force, viz., lines cutting only the rotor windings:

$$= \xi n_r I_k \sin at$$

$$n_r = \text{Conductors round rotor,}$$

$$\xi = \text{Leakage co-efficient.}$$

These lines of force induce on short-circuit an e.m.f.

$$= -\xi n_r^2 I_k . N . \cos at \ 10^{-8} \text{ volts.}$$

The lines of force in the direction $c\ d$ which enter from the rotor into the stator we designate,

$$= B . \sin (at + \beta)$$

and those which in direction $b\ a$ cut the rotor winding (sum of leaking and useful lines),

$$= A. \sin\ (at + \alpha).$$

In these two last formulas, A and B are *the lines per pole,* and β and α the difference of phase of these lines and the current I .
The lines B induce in the short-circuit an e.m.f.,

$$= -B\ N\ n_r \cos\ (at + \beta)\ \ 10^{-8} \text{ volts.}$$

The lines A induce in the same circuit on account of the motion (this assumed clockwise),

$$= A.\ N_1.\ n_r \sin\ (at + \alpha).\ \ 10^{-8} \text{ volts.}$$

N_1 being the speed (in frequency). In the last two formulas it is

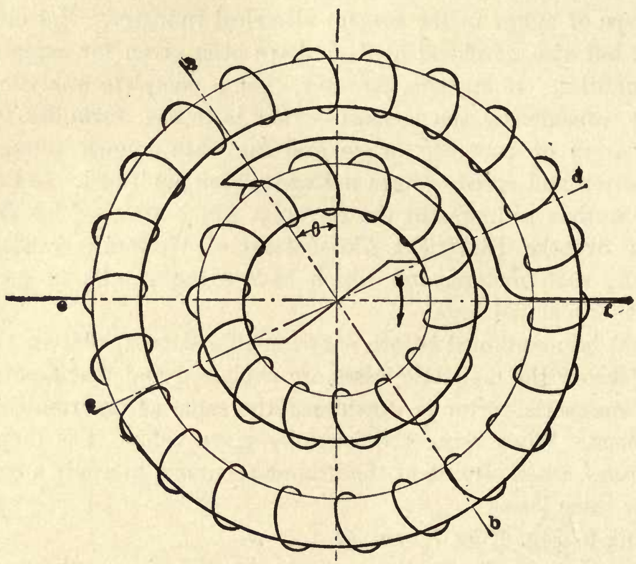


FIG. 1.

assumed that the rotor winding is either two-pole or series-connected, so that each conductor carries a current $= \dfrac{I_k}{2}$. If now $r =$ ohmic resistance of short-circuit, then

$$I_k r \sin at\ 10^8 = A.\ N_1\ n_r \sin\ (at + \alpha) - B.\ n_r \cos\ (at + \beta) - \xi n_r^2 I_k N \cos at$$

This equation must be valid for any value on t, accordingly,

$$I_k .\ r.\ 10^8 = A.\ N_1 .\ n_r \cos \alpha + B\ \ N\ n_r \sin \beta. \qquad (1)$$

$$A.\ N_1\ \sin \alpha = B.\ N. \cos \beta + \xi .\ n_r^2 .\ N. \qquad (\ )$$

In the stator circuit there flows a current, the phase of which

is the same as that of the lines of force A, these lines being caused only by this current. This current we may represent by

$$I. \sin\,(at+\alpha).$$

The direction is positive when the current in the rotor winding flows *from b to a.* This current causes following lines of force:

I. Lines of force cutting only the rotor windings:

$$= \xi\,.\,n_r\,.\,I.\,\sin\,(at+\alpha)$$

in direction $b\ a$.

II. Lines of force cutting both rotor- and stator-winding in direction b a:

$$= \zeta.\ \mathrm{I}.\ \sin\,(at+\alpha)\,(n_r - n_s\,.\,\sin\theta)$$

ζ is a co-efficient depending on the geometrical form of the machine and the permeability of the iron; n_s = number of conductors on stator, the same assumption being made as for n_r, viz., that each conductor carries a current $= \frac{\mathrm{I}}{2}$. θ = angle of brush position (see Fig. 1).

The sum of these lines of force must equal $A.\ \sin\,(at+\alpha)$. Accordingly

$$A = I.\,[\zeta\,(n_r - n_s\,.\,\sin\theta) + \xi.\,n_r\,]$$

$$\text{or:}\quad A = I.\,D$$

$$\text{if:}\quad D = \zeta\,\,(n_r - n_s\,.\,\sin\theta) + \xi.\,n_r\,.$$

The lines cutting both stator and rotor winding in direction $c\ d$ are caused by the combined influence of ampere-turns in stator and rotor. Hence:

$$B.\,\sin\,(at+\beta) =$$
$$\zeta\,[n_s\,.\,I.\,\sin\,(at+\alpha).\,\cos\theta + I_k\,.\,n_r\,.\,\sin at]\ldots \quad (1)$$

This equation is valid for any value of the angle $a\ t$, therefore:

$$\sin at\,(B.\,\cos\beta - \zeta.\,n_s\,I.\,\cos\theta\ -\ \zeta.\,n_r\,I_k) = 0\ldots\ldots \quad (2)$$
$$\cos at\,(B.\,\sin\beta - \zeta.\,n_s\,I.\,\sin\alpha.\,\cos\theta) = 0\ldots\ldots\ldots \quad (3)$$

and

$$B.\,\cos\beta - \zeta.\,n_s\,I.\,\cos\alpha.\,\cos\theta - \zeta.\,n_r\,I_k = 0\ldots\ldots \quad (4)$$
$$B.\,\sin\beta - \zeta.\,n_s\,I.\,\sin\alpha.\,\cos\theta = 0\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

The equations 1, 2, 3, 4 and 5 contain, besides I, five unknown quantities A, B, α, β and I_k, and hence give values of these expressed in I and known numbers.

Now combining equations (1) and (2), then (1) with (4), and afterward eliminating B by means of (5) and A by means of (3), we get:

$$\cot \alpha = \frac{\frac{N_1 . r\ D}{\zeta . N} . 10^8 - N . n_r^2 . n_s . \cos\theta\,(\zeta + \xi)}{r . n_s . \cos\theta . 10^8 + N_1 . n_r^2 . D\left(1 + \frac{\xi}{\zeta}\right)} \quad \ldots (6)$$

$$\cot \beta = \frac{D . N_1}{\zeta . n_s . \cos\theta}\left[\frac{1}{N} - \frac{\xi . n_r^2 . \cot \alpha}{r . 10^8}\right] - \frac{N . n_r^2 . \xi}{r . 10^8} \quad \ldots (7)$$

These equations show that α and β are independent of the current.

From (4) and (5) we obtain

$$B = \frac{\zeta . n_s\ I . \sin \alpha . \cos\theta}{\sin\beta} \quad \ldots\ldots (8)$$

$$I_k = \frac{n_s . I . \sin \alpha . \cos\theta}{n_r}(\cot\beta - \cot\alpha) \quad \ldots\ldots (9)$$

In the stator circuit, the induced e.m.f's. are:

I. In the rotor winding, by the lines of force along c d:

$$= -[\xi . n_r . I_k . \sin at + B . \sin(at + \beta)] . N_1 . n_r . 10^{-8}.$$

II. In the rotor winding, by the lines of force along b a:

$$= - A . \cos(at + \alpha) . N . n_r . 10^{-8}.$$

III. In the stator winding, by the lines of force along b a:

$$= \zeta . I . \cos(at + \alpha)(n_r - n_s . \sin\theta) . N . n_s . \sin\theta . 10^{-8}.$$

IV. In the stator winding, by the lines of force along c d:

$$= - B . \cos(at + \beta) . N . n_s . \cos\theta . 10^{-8}.$$

V. In the stator winding, by self-induction:

$$= - I . \cos(at + \alpha)\, n_s^2\, \lambda . N . 10^{-8}.$$

λ = Leakage co-efficient corresponding to ξ.

VI. Influence of ohmic resistance:

$$= - I . \sin(at + \alpha) . R.$$

R = total resistance of stator circuit (including rotor winding, brushes, etc.). If now the machine acts as a motor, then the impressed e.m.f. must equal the sum of above six expressions with opposite signs.

Accordingly, if E = voltage at terminals of motor (amplitude), and γ its phase:

$$\begin{aligned}- E \sin(at + \gamma) . 10^8 = {} & - I . \sin(at + \alpha) . R . 10^8. \\ & - I . \cos(at + \alpha)\, n_s^2 . \lambda . N - B . \cos(at + \beta) . N . n_s \cos\theta \\ & + \zeta . I . \cos(at + \alpha)(n_r - n_s . \sin\theta) . N . n_s . \sin\theta \\ & - A . \cos(at + \alpha) . N . n_r \\ & - [\xi . n_r . I_k . \sin at + B . \sin(at + \beta)]\, N_1 . n_r \quad \ldots\ldots (10)\end{aligned}$$

Now substituting for A, B and I_k their values [equations (3), (8), (9)]

$$\frac{E}{I}. \sin (at + \gamma) = R. \sin (at + \alpha) + V. \cos (at + \alpha)$$
$$+ W. \cos (at + \beta) + U. \sin (at + \beta) + T. \sin at \ldots. \quad (11)$$

in which

$V = [n_s^2. \lambda. N - \zeta. N. n_s. \sin \theta \, (n_r - n_s \sin \theta) + N. n_r D]. 10^{-8}$

$W = \zeta. n_s^2. \sin \alpha. \cos^2 \theta. N. 10^{-8}$

$U = \zeta. n_s. \sin \alpha. \cos \theta. N_1. n_r. 10^{-8}$

$T = \xi. n_r. N_1. n_s. \cos \theta \, (\cot \beta - \cot \alpha). 10^{-8}.$

Developing the goniometric functions of the sums $(at + \alpha)$ and $(at + \beta)$ and considering that the equation (11) is valid for any value of at we get:

$$I = \frac{E}{\sqrt{P^2 + Q^2}} \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

and

$$\tan \gamma = \frac{P}{Q},$$

in which expressions

$$P = R. \sin \alpha + V. \cos \alpha + W. \cot \beta + U$$
$$Q = R. \cos \alpha - V. \sin \alpha - W + U. \cot \beta + T. \sin \alpha.$$

These equations give values of current and λ when voltage, frequency and speed are known.

Though I and E have been defined as amplitudes of current and e.m.f. the equation (12) of course also holds good for effective values.

The angle by which the current I is in advance being α and γ, the angle by which the terminal voltage is in advance, both relating to the same epoch, then the angle of lag of current behind e.m.f. is

$$\varphi = \lambda - \alpha.$$

Calculation of Torque.

I. Torque from lines of force along $a\,d$ and current I, clockwise:

$$= B. \sin (at + \beta). n_r . I. \sin (at + \alpha). p. \frac{0.1}{2\pi}.$$

dynes at 1 cm radius, p = number of pairs of poles.

The integrated average value during a period calculated from above expressions is

$$= \frac{B. I. \cos (\alpha - \beta). n_r . p. 0.1}{4.\pi}.$$

II. Torque from lines of force along ba and current I_k, clockwise:

$$= - \zeta . I . \sin (at + \alpha) (n_r - n_s \sin \theta) . n_r I_k . \sin at . p . \frac{0.1}{2\pi}$$

dynes at 1 cm radius. Average value

$$= - \frac{\zeta . I . (n_r - n_s . \sin \theta) . n_r . I_k . \cos \alpha . p . 0.1}{4.\pi} .$$

The resulting torque is the sum of the above expressions. Substituting for I_k and B their values, we obtain:

$$\frac{\zeta . I^2 . n_s . \sin \alpha . \cos \alpha . \cos \theta \; p}{40.\pi} \begin{bmatrix} n_r (\tan \alpha + \cot \alpha) \\ + n_s . \sin \theta (\cot \beta - \cot \alpha) \end{bmatrix}$$

and expressed in kilograms at 1 meter radius with current expressed in effective amperes, after some transformation:

$$K = 1.625 . 10^{-10} \zeta . I_e^2 . n_s . \cos \theta . p . [n_r + n_s . \sin \theta \\ (\sin \alpha . \cos \alpha . \cot \beta - \cos^2 \alpha)]$$

The formulæ thus obtained suffice for figuring the behavior of a motor, if its design is given. The magnetic induction in the directions $b\ a$ and $c\ d$ can also be calculated, and accordingly corrections can be made for the iron losses.

Motors of this kind are generally used for such purposes where it is necessary that they can work in both directions. This being the case, it is of advantage to arrange the machinery in such a way that no shifting of brushes is necessary. If θ is made $= 0$, the position of the brushes is perfectly symmetrical and accordingly allows the motor to run in any direction. But if $\theta = 0$, the formulas are also greatly simplified. At the end of the paper a summary of the formulas is given, not only in their most general form, but also for $\theta = 0$.

Maximum Torque at Start.

Supposing that from the reasons just stated, we use the arrangement with a symmetrical brush position ($\theta = 0$); then it is of interest to investigate what relation n_r should have to n_s, the latter being given, in order to get maximum starting torque.

Accordingly, a motor with known n_s, ζ, ξ, etc., is given; for what value of n_r is the maximum torque obtained at $N_1 = 0$?

Substitute in the formulas,

$$\theta = 0; N_1 = 0; n_r = n_s . c \text{ then}$$

$$D = c . n_s (\zeta + \xi)$$

$$\cot \alpha = \frac{-N.\, c^2.\, n_s^2.\, (\zeta + \xi)}{r.\, 10^8}$$

$$\cot \beta = -\frac{N.\, c^2.\, n_s^2.\, \xi}{r.\, 10^8}$$

$$V = N.\, n_s.^2 \,[\lambda + c^2 \,(\zeta + \xi)]$$

The angle α (difference of phase of stator and rotor current) is at starting a little less than 180 degs. Accordingly, we may write,

$$\sin \alpha = -\frac{1}{\cot \alpha}$$

$$W = \frac{\zeta.\, r.\, 10^8}{c^2 \,(\zeta + \xi)}$$

$$U = 0$$

$$T = 0.$$

If we now neglect the quantities which contain r and R, then,

$$I_2 = \frac{E^2}{\left\{ N.\, n_s^2 \,[\lambda + c^2 \,(\zeta + \xi)] \cos \alpha - \dfrac{\zeta.\, N.\, n_s^2\, \xi}{\zeta + \xi} \right\}^2 + \left\{ N.\, n_s^2 \,[\lambda + c^2 \,(\zeta + \xi)] \sin \alpha \right\}^2}.$$

Seeing now that α is a trifle less than 180 degs., then $\cos \alpha = \sim -1$ and $\sin \alpha = \sim 0$

The denominator, therefore, becomes:

$$\left\{ N.\, n_s^2 \right\}^2 . \left\{ [\lambda + c_2 \,(\zeta + \xi)] + \frac{\zeta.\, \xi}{\zeta + \xi} \right\}^2$$

and the expression for the torque is

$$K = \frac{c}{\left[\lambda + c^2 \,(\zeta. + \xi) + \dfrac{\zeta.\, \xi}{\zeta + \xi}\right]^2} \times \text{a constant.}$$

Differentiating:

$$\frac{dK}{dc} = \left[\lambda + c^2 \,(\zeta + \xi) + \frac{\zeta\, \xi.}{\zeta + \xi}\right]^2 - 4c^2 \left[\lambda + c^2 (\zeta + \xi) + \frac{\zeta.\, \xi}{\zeta + \xi}\right] (\zeta + \xi) = 0$$

(denominator of differential coefficient omitted, not possibly being $= 0$).

As now the expressions in brackets could not be $= 0$ (containing only positive quantities), then for maximum torque:

$$\lambda + c^2 . \,(\zeta + \xi) + \frac{\zeta\, .\, \xi}{\zeta + \xi} - 4c^2 \,(\zeta + \xi) = 0$$

$$\therefore c = \sqrt{\frac{\lambda + \dfrac{\zeta\, .\, \xi}{\zeta + \xi}}{3\,(\zeta + \xi)}}\,.$$

If $\lambda = \xi$ and small in comparison to ζ, then

$$c = 0.82\sqrt{\frac{\xi}{\zeta}}.$$

For a railway motor, which for mechanical reasons cannot have a very small air-gap, $\frac{\xi}{\zeta}$ may come out something like 1/20 which corresponds to $c = 0.183$. *Accordingly, the number of conductors on rotor should be 1/5—1/6 of the number of conductors on stator.*

At starting $\frac{\xi}{\zeta}$ often may, on account of saturation of iron, increase up to 1/6; this would correspond to $c = 0.82\sqrt{1/6} = 0.335$ or the *number of rotor conductors is about one-third of the stator conductors.*

Maximum Torque per Voltampere at Start.

It may be of still more interest to investigate what relation n_r must have to n_s in order to obtain the *maximum torque per voltampere* at start. That is to say, if the voltage is kept constant, the *maximum torque per ampere at start.* The expression for this quantity is easily obtained:

$$\delta = \frac{c}{\lambda + c^2 . (\zeta + \xi) + \frac{\zeta . \xi}{\zeta + \xi}}$$

$$\text{For } \delta = \text{maximum} ; \frac{d\,\delta}{d\,c} = 0$$

$$\therefore \frac{d\,\delta}{d\,c} = \lambda + c^2 . (\zeta + \xi) + \frac{\zeta . \xi}{\zeta + \xi} - 2\,c^2\,(\zeta + \xi) = 0$$

$$c = \sqrt{\frac{\lambda + \frac{\zeta . \xi}{\zeta + \xi}}{\zeta + \xi}}$$

or if $\xi = \lambda$ and small compared with ζ,

$$c = 1.41\sqrt{\frac{\xi}{\zeta}}$$

For $\frac{\xi}{\zeta} = \sim \frac{1}{6}$ then $c = \sim 0.57$; For $\frac{\xi}{\zeta} = \sim \frac{1}{20}$ then $c = \sim 0.32$. *Accordingly, if we wish to obtain the greatest economy with current at start, the number of rotor conductors must be chosen larger than if the greatest torque is aimed at.*

It should be pointed out that for other reasons (considerations as to lag, etc.), the number of rotor conductors often must be somewhat modified.

Finally, the results of experiments with a motor of this kind will be given. The machine was made by the Allmänna Svenska Elektriska Aktiebolaget, Westerås, and tested in their works.

The stator of this experimental machine (see Fig. 2) had 72

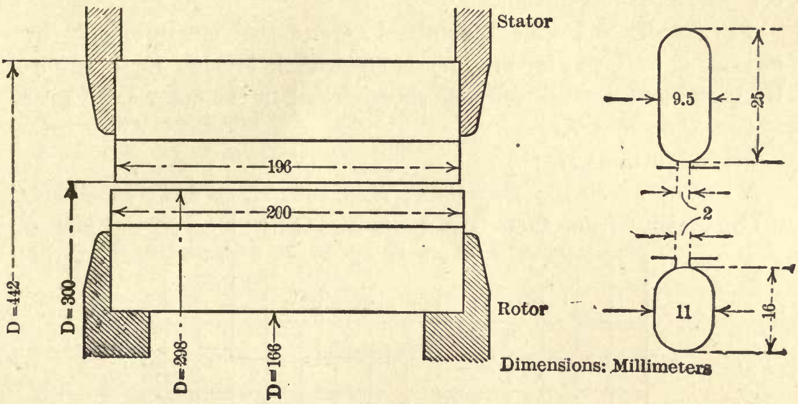


FIG. 2.

half-open slots, each containing 12 conductors of 2.5 mm diameter. The winding was divided in two groups which were connected in parallel. The rotor had 49 slots with 6 wires of 2.8 mm diameter. Winding, series drum. Number of poles, 4. Air-gap, 1 mm. Frequency, 27. Voltage, 200.

Calculation of ζ.

A current in the rotor winding $= I$ causes a flow of lines in the air-gap (neglecting iron) per pole:

$$\frac{n_r}{4} . \frac{I}{2} . \ 1.25 . \frac{1}{0.2} . \ 459 . \frac{1}{2}$$

(459 = area of 1 pole).

Accordingly:

$$\zeta . \ I . \ n_r = \frac{n_r}{4} . \frac{I}{2} . \ 1.25 . \frac{1}{0.2} . \ 459 . \frac{1}{2}$$

$$\zeta = 180$$

Calculation of $\xi = \lambda$.

The constants of *Hobart* (see Elektrotechnische Zeitschrift No. 46, 1903), are used:

$$\xi . I . n_r = \frac{I}{2} . \frac{n_r}{4} (20 \times 0.93 + 0.4 \times 30) . 2$$

20 = length of one conductor in iron in cms.

30 = free length of one conductor in iron in cms.

0.93 = Hobart's constant.

0.4 = Hobart's constant.

The constants ζ and ξ obtained from actual measurement (by measuring voltage and primary current with brushes removed entirely in one case and complete short-circuit in the other case) are:

$\zeta = 208$; $\xi = 7.1$.

Other constants are:

$N = 27$; $r = 0.15$; $R = 0.68$; $E = 200$; $n_s = 864$; $n_r = 294$.

Calculating from these constants and with $\theta = O$, the curves

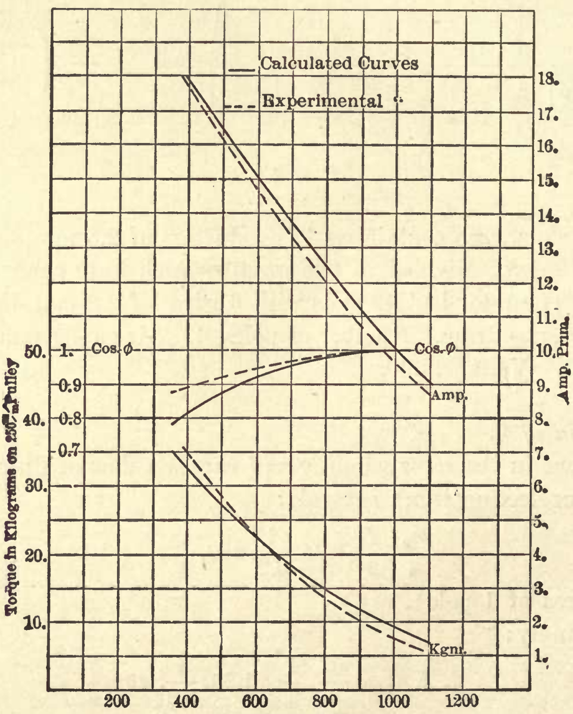


FIG. 3.

in full line (Fig. 3) are obtained. The dotted lines represent the experimental values.

APPENDIX.

SUMMARY OF FORMULAS.

General Formulas.

$$D = \zeta\,(n_r - n_s \sin\theta) + \xi .\, n_r$$

$$\cot\alpha = \frac{\dfrac{N_1\, r\, D\ 10^8}{\zeta .\, N} - N\, n_r^2\, n_s \cos\theta\,(\xi + \zeta)}{r\, n_s \cos\theta\,.10^8 + N_1\, n_r^2\, D\left(1 + \dfrac{\xi}{\zeta}\right)}$$

$$\cot\beta = \frac{D.\ N_1}{\zeta\, n_s \cos\theta}\left[\frac{1}{N} - \frac{\xi\, n_r^2 \cot\alpha}{r.\ 10^8}\right] - \frac{N\, n_r^2\, \xi}{r.\ 10^8}$$

$$V = [n_s \lambda\, N - \zeta\, N\, n_s \sin\theta\,(n_r - n_s \sin\theta) + N\, n_r\, D].10^{-8}$$

$$W = \zeta\, n_s^2 \sin\alpha \cos^2\theta\ N.\ 10^{-8}$$

$$U = \zeta\, n_s \sin\alpha \cos\theta\ N_1\, n_r\,.10^{-8}$$

$$T = \xi\, n_r\, N_1\, n_s \cos\theta\,(\cot\beta - \cot\alpha)\,.10^{-8}$$

$$P = R. \sin\alpha + V. \cos\alpha + W. \cot\beta + U$$

$$Q = R. \cos\alpha - V \sin\alpha - W + U. \cot\beta + T \sin\alpha$$

$$tan = \frac{P}{Q}$$

$$\varphi = \gamma - \alpha$$

$$I_e = \frac{E_e}{\sqrt{P^2 + Q^2}}$$

$$I_{ek} = \frac{n_s\ I_e\ \sin\alpha.\ \cos\theta\,(\cot\beta - \cot\alpha)}{n_r}$$

$$K = 1.625\ 10^{-10}.\ \zeta\, I_e^2.\ n_s \cos\theta.\ p\,[n_r + n_s \sin\theta\,(\sin\alpha.\ \cos\alpha \cot\beta - \cos^2\alpha)]$$

Special Formulas.

for $\theta = O$.

$$D = n_r\,(\zeta + \xi)$$

$$\cot\alpha = \frac{\dfrac{N_1\, r\, D.\ 10^8}{\zeta\, N} - N\, n_r^2\, n_s\,(\zeta + \xi)}{r\, n_s\, 10^8 + N_1\, n_r^2\, D\left(1 + \dfrac{\xi}{\zeta}\right)}$$

$$\cot\beta = \frac{D.\ N_1}{\zeta\, n_s}\left[\frac{1}{N} - \frac{\xi.\ n_r^2.\ \cot\alpha}{r.\ 10^8}\right] - \frac{N\, n_r^2\, \xi}{r.\ 10^8}$$

$$V = [n_s^2 \lambda\, N + N\, n_r\, D].\ 10^{-8}$$

$$W = \zeta.\ n_s^2 \sin\alpha\ N.\ 10^{-8}$$

$$U = \zeta\ n_s\ \sin\alpha.\ N_1\, n_r.\ 10^{-8}$$

$$T = \xi\ n_r\, N_1\, n_s\,(\cot\beta - \cot\alpha).\ 10^{-8}$$

$$P = R. \sin\alpha + V \cos\alpha + W \cot\beta + U$$

$$Q \quad = R. \cos \alpha - V \sin \alpha - W + U \cot \beta + T \sin \alpha.$$

$$tan\ \gamma = \frac{P}{Q}$$

$$\varphi \quad = \gamma - \alpha$$

$$I_e \quad = \frac{E_e}{\sqrt{P^2 + Q^2}}$$

$$I_{ek} \quad = \frac{n_s I_e . \sin \alpha (\cot \beta - \cot \alpha)}{n_r}$$

$$K \quad = 1.625.\ 10^{-10} \zeta .\ I_e{}^2 n_s p\ n_r$$

Notation.

D = a coefficient.

n_r = number of conductors round rotor, provided the winding is such that each conductor carries half of current on short-circuit. If the rotor has a six-pole parallel winding, then n_r = active conductors divided by three.

n_s = number of conductors on stator, provided that each conductor carries half of total current.

ζ = coefficient of magnetization; $\zeta\ n_s$ = number of lines of force per pole at one ampere in stator circuit, with no current in rotor.

ξ = coefficient of leakage; $\xi\ n_r$ = leaking lines per pole at one ampere on short-circuit.

λ = leaking coefficient for stator.

θ = angle of brush position.

α = angle of lag between current in stator circuit and short-circuit.

β = angle of lag between lines of force along $b\ c$ and short-circuited current.

N = frequency.

N_1 = speed expressed in frequency (at synchronous speed $N_1 = N$).

r = resistance of rotor circuit including short-circuit.

R = resistance of short-circuit including rotor winding.

V, W, U, T, P and Q = coefficients.

I_e = stator current (effective value).

I_{ek} = short-circuited current (effective value).

E_e = impressed e.m.f. (effective value).

K = torque in kilograms at 1 meter radius.

INDEX OF SUBJECTS.

w50 net